JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D05313, doi:10.1029/2005JD006198, 2006

Spatial and temporal patterns of carbon emissions from forest fires in China from 1950 to 2000

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Received 10 May 2005; revised 25 August 2005; accepted 2 December 2005; published 11 March 2006.

[1] We have estimated the emission of carbon (C) and carbon-containing trace gases including CO_2, CO, CH_4, and NMHC (nonmethane hydrocarbons) from forest fires in China for the time period from 1950 to 2000 by using a combination of remote sensing, forest fire inventory, and terrestrial ecosystem modeling. Our results suggest that mean annual carbon emission from forest fires in China is about 11.31 Tg per year, ranging from a minimum level of 8.55 Tg per year to a maximum level of 13.9 Tg per year. This amount of carbon emission is resulted from the atmospheric emissions of four trace gases as follows: (1) 40.66 Tg CO_2 with a range from 29.21 to 47.53 Tg, (2) 2.71 Tg CO with a range from 1.48 to 4.30 Tg, (3) 0.112 Tg CH_4 with a range from 0.06 to 0.2 Tg, and (4) 0.113 Tg NMHC with a range from 0.05 to 0.19 Tg. Our study indicates that fire-induced carbon emissions show substantial interannual and decadal variations before 1980 but have remained relatively low and stable since 1980 because of the application of fire suppression. Large spatial variation in fire-induced carbon emissions exists due to the spatial variability of climate, forest types, and fire regimes.

Citation: Lü, A., H. Tian, M. Liu, J. Liu, and J. M. Melillo (2006), Spatial and temporal patterns of carbon emissions from forest fires in China from 1950 to 2000, *J. Geophys. Res.*, *111*, D05313, doi:10.1029/2005JD006198.

1. Introduction

[2] Forest ecosystems play an important role in the global carbon cycle. They store nearly two thirds of the terrestrial C in vegetation and soil [*Dixon et al.*, 1994] and have huge capacity to sequestrate atmospheric carbon dioxide [*Brown et al.*, 1996]. Quantifying the sinks and sources of carbon in forest ecosystems is essential to balancing the global carbon budget. Some studies have addressed ecosystem processes that control carbon sinks in the terrestrial ecosystems [*Melillo et al.*, 1993; *Tian et al.*, 1998; *Schimel et al.*, 2000]. Other analyses have emphasized the role of deforestation on carbon sources from terrestrial ecosystems [*Houghton and Hackler*, 2003; *Tian et al.*, 2003]. However, natural disturbance, which is an important factor in controlling carbon sink/source behavior, has often been ignored. Fully understanding the mechanisms controlling carbon exchange between terrestrial ecosystems and the atmosphere needs to take into account natural disturbances, especially fires [*Kasischke et al.*, 1995b; *McGuire et al.*, 2001].

[3] Disturbance is defined as any relatively discrete event in time that disrupts the ecosystem, community, or population structure and changes in resources, substrate availability, or the physical environment [*Pickett and White*, 1985]. Fire is the primary disturbance in many forest ecosystems [*Fraser and Li*, 2002]. Fire can reallocate carbon among different carbon pools by influencing ecosystem structure and processes [*Kasischke and French*, 1997; *Peng and Apps*, 1999; *Richter et al.*, 2000; *Shvidenko and Nilsson*, 2000a, 2000b; *Andreae and Merlet*, 2001; *Wardle et al.*, 2003; *O'Neill et al.*, 2003; *Andersson et al.*, 2004; *Lü et al.*, 2005]. The influences of fire on the carbon cycle include both the direct release of carbon-containing trace gases into atmosphere through biomass burning and indirect impacts on net primary productivity and microbial decomposition processes. Fire alters stand-age distribution, species composition and soil biogeochemical properties [*Kasischke*, 2000a; *Morrissey et al.*, 2000]. Postfire effect on the regional carbon budget is perhaps more important than carbon emission from biomass burning [*Conard and lvanova*, 1997; *Kurz and Apps*, 1999; *Kasischke*, 2000a; *Hicke et al.*, 2003]. Biomass burning is one of the immediate direct carbon-released agents, which convert living or dead biomass into carbon-containing trace gases, such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) and nonmethane hydrocarbons (NMHCs). Fire-induced emissions have significantly contributed to the variations of the atmospheric concentrations of carbon-containing trace gases [*Wotawa and Trainer*, 2000; *Schimel and Baker*, 2002; *Langenfelds et al.*, 2002; *van der Werf et al.*, 2004].

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0148-0227/06/2005JD006198$09.00

[4] Wildfire and climate are intimately linked each other [*Swetnam*, 1993]. The fire-induced trace gases, especially CO_2 and CH_4, can influence the global climate. Changing climate, on the other hand, may be accompanied by increasing fire hazard, higher fire frequency, and longer fire seasons [*Swetnam*, 1993; *Kasischke et al.*, 1995a; *Conard and lvanova*, 1997; *Campbell and Flannigan*, 2000; *Stocks et al.*, 2000; *Li et al.*, 2003]. To accurately estimate fire-induced carbon emission therefore is important for improving our understanding of the interaction between climate and the carbon cycle. Many efforts have been made to estimate the magnitude of fire-induced carbon emissions at regional, national and continental scales [*Wong*, 1978; *Crutzen et al.*, 1979; *Cahoon et al.*, 1994; *Kasischke et al.*, 1995a, 2000; *Wang et al.*, 1996, 2001a; *Conard and Ivanova*, 1997; *French et al.*, 2000; *Andreae and Merlet*, 2001; *Korontzi et al.*, 2003; *Liu*, 2004].

[5] China, the third largest country in land area with great variability in physical environment, has experienced substantial climate variation and dramatic land transformation across the nation [*Tian et al.*, 2003; *Liu et al.*, 2005]. These changes in climate and land use could change fire regime in forest ecosystems and hence the magnitude of fire-induced carbon emission. Some previous studies have investigated the effect of forest fires on forest ecosystems at local level [e.g., *Cahoon et al.*, 1994], which was focused on specific fire. Other analyses used statistical methods to estimate national-level emission of carbon from forest fires but did not fully consider the spatiotemporal variability of input data and parameters in their national-scale estimate [e.g., *Wang et al.*, 2001a]. The purpose of this study is to examine the spatial (grid, regions) and temporal (annual, decadal) patterns of the fire-induced carbon emissions in Chinese forests during 1950 to 2000 by using a combination of an improved fire-induced carbon emission model, remotely sensed data, forest fire inventory data, and terrestrial ecosystem model. We also try to identify gaps and limitations in existing data and methods that need to be investigated in the future to improve our understanding of fire's role in regional carbon dynamics.

2. Method and Data

[6] We generated a spatially explicit estimate on carbon emission from forest fires by using a refined fire emission model and considering spatial variability in fire-related parameters (e.g., combustion efficiency, emission factors) and fire-scar properties (e.g., forest type, vegetation biomass). In this section, we describe the calculation of the fire-induced immediate carbon emission and the development of spatial data.

2.1. Fire-Induced Immediate Carbon Emission Model

[7] The estimation of fire-induced immediate carbon emission (C) is usually based on the *Seiler and Crutzen* [1980] model:

$$C = ABf_c\beta, \tag{1}$$

where A is the total area burned (ha), B is the biomass density (t ha^{-1}), f_c is the carbon fraction of the biomass, and β is the fraction of biomass consumed (or combustion efficiency) during biomass burning.

[8] Carbon emissions estimated by equation (1) are usually lower than the real values because the burning of forest floor fuels such as litter, lichen, and organic soils etc. are ignored in the equation. The combustion properties of these floor fuels are believed to be different from those of the aboveground vegetation and are contribute to the carbon emissions of forest fires, especially for the boreal forests [*French et al.*, 2000; *Kasischke and Bruhwiler*, 2003]. Here we modified equation (1) based on the modification of *French et al* [2000] and *Kasischke and Bruhwiler* [2003]:

$$C = A\left(C_a\beta_a + C_g\beta_g\right). \tag{2}$$

where C_a is the average carbon density of aboveground vegetation (t ha^{-1}), β_a is the fraction of aboveground vegetation consumed during fires, C_g is the carbon density (t ha^{-1}) of floor fuels, and β_g is the fraction of floor fuels consumed during fires.

[9] The amount of each specific trace gas released during fires (E_s) can be estimated as

$$E_s = CE_{fs}, \tag{3}$$

where E_{fs} is the emission factor (in weight of gas released per weight of carbon burned) for the gases species. In this study, we assumed that parameters, β_a, β_g, and E_{fs}, are closely related to the forest types.

[10] We calculated the mean, minimum, and maximum levels of the fire-induced emissions in correspondence with the variations of combustion efficiency and emission factor. The fire-induced emissions for each forest grid were estimated. The grid-level estimates of carbon emissions were then summed up to get estimates on the regional and national levels.

2.2. Data and Parameters

[11] The development of spatially explicit data sets is essential to examine the spatial patterns of fire-induced carbon emissions. We built up the spatial data sets based on various sources from remote sensing imagery, model simulations, field observations, census record, and literatures. Major spatial data sets we used for our study include forest cover, fire location and burned area, and forest biomass. Two key parameters we used are combustion efficiency and emission factor. Below is the description of how we generated these data sets and parameters.

2.2.1. Forest Cover

[12] Information on forest distribution is fundamental for spatially estimating biomass and determining fire-related parameters. We developed our historical forest cover data based on remotely sensed data, forest inventory data, and cropland and urban area.

[13] The forest cover data for the time period from 1990 to 2000 are based on the land-cover data sets (1:100,000), which are derived from Landsat TM/ETM imagery at a resolution of 30 m for 3 years of 1990, 1995, and 2000 [*Liu et al.*, 2005]. In this analysis, we aggregated this forest cover data to raster format with the grid size of 10 km × 10 km (Figure 1a). In each grid, there is information on the area percentages of all land-use types. Then we extracted

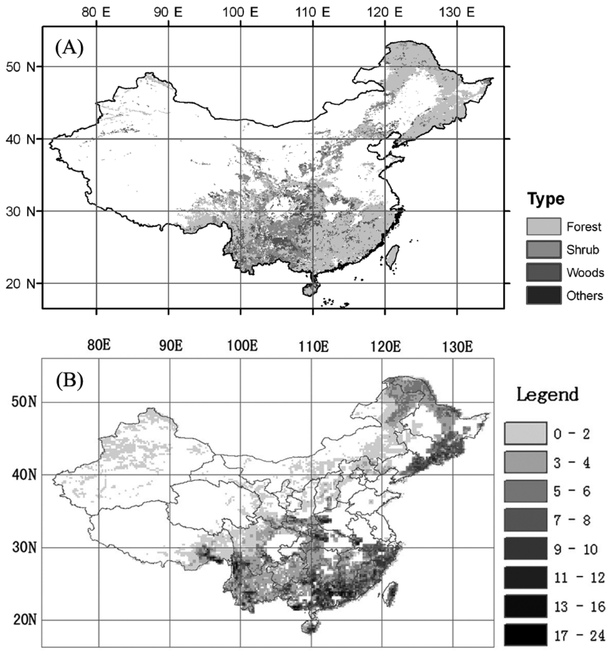

Figure 1. Contemporary patterns of forest cover and biomass in China. (a) Distribution of forest cover in 2000 derived from Landsat ETM [*Liu et al.*, 2005]. Forest cover includes all lands growing trees including arbor, shrub, bamboo, and for forestry use. (b) Distribution of forest biomass (Tg C) in 2000 across China based on estimates by the Terrestrial Ecosystem Model [*Tian et al.*, 2003].

the forest cover data from these raster data sets and classified them according to their respective forest types using a Chinese vegetation map (1:4,000,000) [*Hou*, 1979]. According our analysis, China's forests covered about 137.6 Mha in 2000 and the distribution of the forests cover vary across different regions [*Liu et al.*, 2005]. Among six subregions in China (Figure 1a), northwest contributes 4.2% of the total, southwest 20.6%, south 22.9%, east 17%, north 13.8%, and northeast 21.5%. Our Landsat-based estimate of forest area in China is lower than the forest area of 158.94 Mha as reported by State Forestry Administration based on surveys using other techniques [*State Forestry Administration*, 2000; *Liu et al.*, 2005]. This discrepancy may be caused by different methods we used.

[14] To generate forest cover data sets for the time period from 1950 to 1989, we used various data sources from the surveys of forest, cropland, and urban as well as remotely sensed data. Recent studies indicated that forest loss in the past several decades was primarily caused by cropland expansion and urbanization [*Ge et al.*, 2000; *Li*, 1999; *Heilig*, 1999; *Wu and Guo*, 1994; *Liu et al.*, 2005]. In this study therefore we assumed that changes in forest area from 1950 to 1990 were primarily caused by the conversion of forest to cropland and urban. We also assume that forests disturbed by fires can be recovered so that fires do not cause a decrease in forest area. The procedure we used to generate historical forest cover data includes the following steps: First, we combined the Landsat-derived land-cover data for the year of 1990 [*Liu et al.*, 2005] with the vegetation map of China [*Hou*, 1979] to create the gridded data of natural vegetation types at a resolution of 10 × 10 km. Second, we developed a gridded historical cropland and urban data set at a resolution of 10 × 10 km for the period from 1950 and 1990 based on the percentage of cropland and urban in each grid in 1990 [*Liu et al.*, 2005] and the statistical data during 1950–1990 at provincial level. Third, we generated the gridded annual forest cover during 1950–1990 by using the gridded data of natural vegetation, and of cropland and urban areas. The gridded annual forest cover data have been modified by forest cover data derived from satellite imagery and forest surveys and have also been evaluated by experts.

2.2.2. Fire Location and Burned Areas

[15] Information on the geographical location of burned areas is crucial to accurately estimate the emissions of carbon and specific trace gases emitted from biomass burning [*Levine and Cofer*, 2000; *Andreae and Merlet*, 2001]. However, as yet the detailed spatial fire data set is only available for a few countries [*Lü et al.*, 2005]. Most countries only have the yearly fire inventory data on provincial or state level. The available data in China from 1950 to 2000 is the fire inventory data (available from State Administration of Forestry, 1949–1987; China Forestry Yearbook Committee, 1989–2001) which does not include more detailed spatiotemporal information but includes only annual burned area and fire times at provincial level. The spatial approach employed in this study requires that burned area should be at a georeferenced grid level. Here we assumed that all forest grids in each province are affected by fires, i.e., the burned percentage at grid level is equal to the ratio of burned area to total forest area at the provincial level. By integrating historical forest cover and forest fire inventory data, forest fires were located in the forest grids at a resolution of 10 × 10 km.

2.2.3. Forest Biomass

[16] The biomass data used in this study is derived from the Terrestrial Ecosystem Model [*Tian et al.*, 2003], which has fully considered the combined effects of climate variation (including temperature, precipitation, and cloudiness), increasing atmospheric CO_2 concentration, and land-use change on the carbon storage of different pools (e.g., vegetation, soil, and litterfall) in Chinese forest ecosystems [*Tian et al.*, 2005]. Figure 1b shows the geographic distribution and temporal pattern of forest biomass estimated by

Table 1. Range of Combustion Efficiency for Each Forest Type in China

	Combustion Efficiency, %	
Forest type	Above Ground	Ground Layer[a]
Tropical forest[b]	25.0(20.0∼30.0)	50.0(3.0∼90.0)
Tropical-subtropical mixed forest	21.5(17.0∼26.0)	50.0(3.0∼90.0)
Subtropical forest	18.0(14.5∼21.0)	50.0(3.0∼90.0)
Temperate-subtropical mixed forest	14.0(12.0∼16.0)	50.0(3.0∼90.0)
Temperate forest[c]	10.5(9.0∼12.0)	50.0(3.0∼90.0)
Boreal forest[d]	25.0(15.0∼34.0)	50.0(3.0∼90.0)

[a] Data sources are *Levine and Cofer* [2000], *Kasischke et al.* [1995a, 1995b, 2000b, 2003], *French et al.* [2000], *Shvidenko and Nilsson* [2000a], *Conard et al.* [2002].

[b] Data sources are *Levine and Cofer* [2000], *Fearnside et al.* [1993], *Seiler and Crutzen* [1980], *Crutzen and Andreae* [1990], *Scholes et al.* [1996].

[c] Data source is *Aulair and Carter* [1993].

[d] Data sources are *Levine and Cofer* [2000], *Kasischke et al.* [1995a, 1995b, 2000b], *Kasischke and Bruhwiler* [2003], *French et al.* [2000].

Table 2. Emission Factor for Each Forest Type of China

Forest Type	Emission Factors,[d] g/kg C			
	CO_2	CO	CH_4	NMHC
Tropical forest[a]	3476 ± 198	229 ± 44	14.96 ± 4.4	17.8 ± 6.6
Tropical-subtropical mixed forest	3545 ± 202	228 ± 58	13.07 ± 4.15	14.35 ± 5.4
Subtropical forest	3614 ± 206	226 ± 71	11.18 ± 3.9	10.9 ± 4.1
Temperate-subtropical mixed forest	3683 ± 210	225 ± 84	9.29 ± 3.6	7.4 ± 2.8
Temperate forest[b]	3752 ± 214	223 ± 97	7.4 ± 3.3	3.9 ± 1.5
Boreal forest[c]	3590 ± 70	296 ± 59	7.8 ± 2.1	4.2 ± 1.9

[a] These data are compiled from *Andreae and Merlet* [2001].

[b] Source: *Laursen et al.* [1992].

[c] Source: *Cofer et al.* [1996], *Levine et al.* [2000], *Laursen et al.* [1992].

[d] When published emission factor follows the same definition as *Andreae and Merlet* [2001], we used default carbon content of 45% to convert it to our definition.

TEM for the year of 2000. A detailed description of how we generated biomass from TEM has been provided elsewhere [*Tian et al.*, 2003, 2005].

[17] To get C_a used in equation (2), we use root to shoot ratio (R/S) [*Klepper*, 1991] to represent the allocation of the vegetation carbon, i.e., above ground carbon to below ground carbon. On the basis of the study of *Li and Li* [1996], we used the biomass ratios of root to shoot (R/S) for major forest types in China as follows: 0.321 for tropical forest, 0.277 for tropical-subtropical mixed forest, 0.3 for subtropical forest, 0.307 for temperate-subtropical mixed forest, 0.297 for temperate forest, and 0.274 for boreal forest. Owing to the data limitation, we take TEM's litterfall carbon as C_g in equation (2) and do not consider the soil organic matter in our fire-induced immediate emission. Thus the estimation may be lower than the actual emission because fires could lead to carbon emission from soil organic matter, especially in the boreal forests.

2.2.4. Combustion Efficiency

[18] The fuels in forests, either the aboveground or on the floor, have variable combustion efficiencies ranging from 0.03 to 0.9, which depends on the moisture and size of fuels, the forest types, intensity and timing of fires, topography, wind, and tree stand age [*Cofer et al.*, 1989; *Kasischke et al.*, 1995a; *Kasischke and Bruhwiler*, 2003; *French et al.*, 2000; *Shvidenko and Nilsson*, 2000b]. To estimate the combustion efficiency which is affected by many factors, two methods have been used in the existing research. One is to determine the combustion efficiency of various forest types from the experimental data in specific forest type, respectively [*Levine and Cofer*, 2000], and the other is to use spatiotemporally averaged values [*Palacios-Orueta et al.*, 2004]. The spatial and temporal variations of combustion efficiency, which is valuable in accurately estimating fire-related emission, were

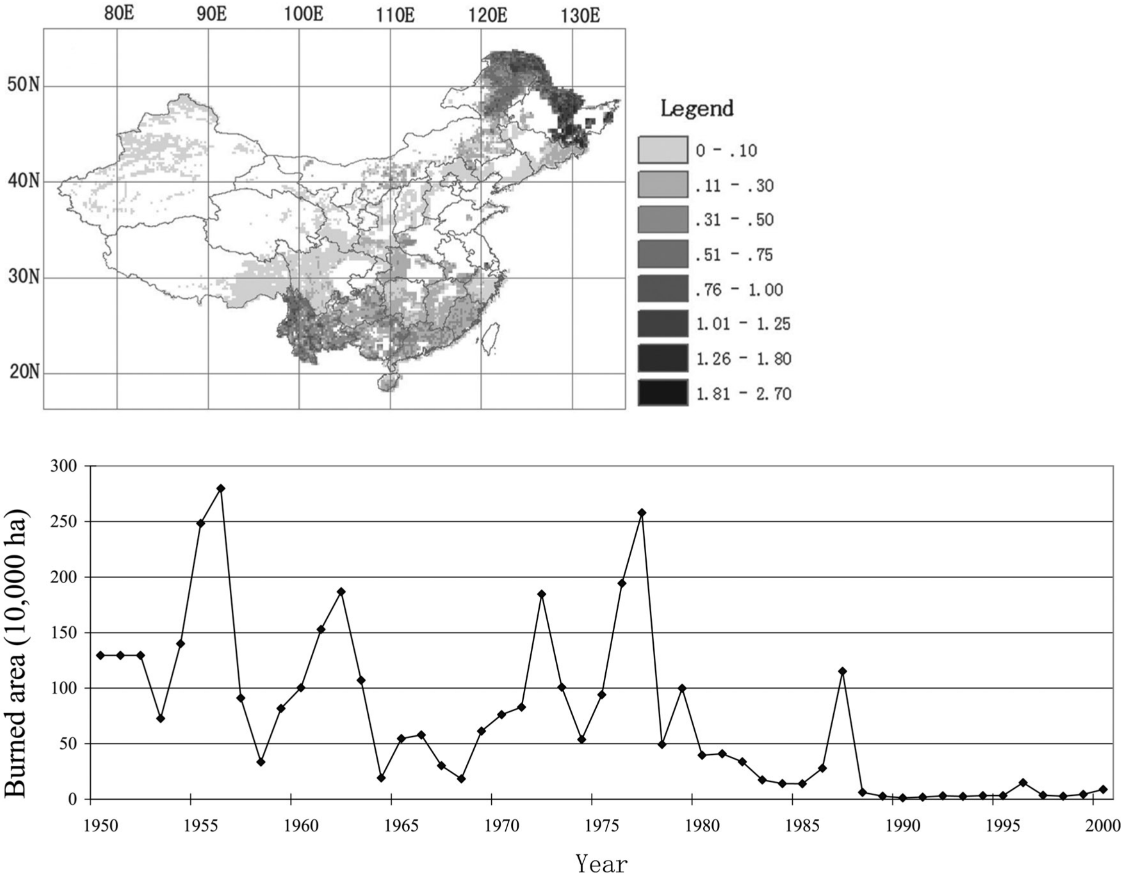

Figure 2. Spatial and temporary patterns of forest area burnt (unit: ha) in China for the time period from 1950 to 2000. (top) Average forest area burnt (1950–2000) and (bottom) annual forest area burnt for the same period.

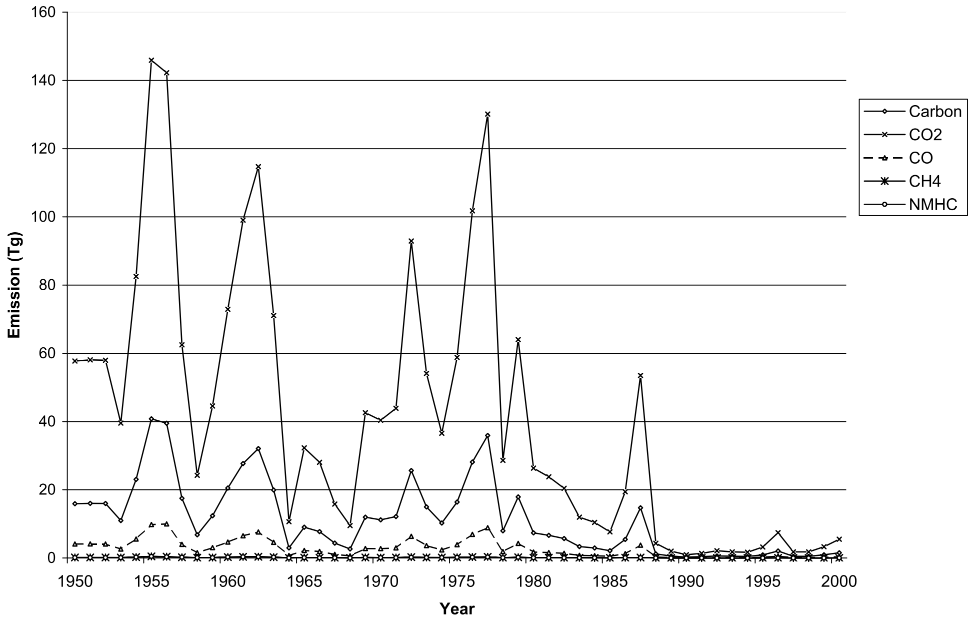

Figure 3. The annual emission of carbon, CO_2, CO, CH_4, and NMHC induced by forest fires in China (1950–2000).

calculated as a function of fuel moisture content, forest type, and other environmental factors. [*Chuvico et al.*, 2004]. However, there are no field data and other related data that is necessary to computing combustion efficiency in China. So in this study we calculated the mean of existing published combustion efficiency through the world for each forest type. For example, in order to estimate the combustion efficiency for the tropical forest in China, we collected not only the published data for the tropical forest in Asia but also those in South American and South Africa. In order to account for the effect of factors other than forest type on combustion efficiency, we then calculated their mean, minimum, and maximum values for each forest type (Tables 1 and 2). The data was not available for transitional forest types, such as the subtropical forest, tropical-subtropical mixed forest, and temperate-subtropical mixed forest. We assumed that they can be represented by the average of two nearby types. For example, the combustion efficiency of subtropical forest is estimated to be the average of tropical forest and temperate forest. For tropical-subtropical mixed forest, the combustion efficiency should be the average of tropical forest and subtropical forest. Combining these data with the Chinese vegetation distribution map, we determined the distribution of forests' combustion efficiency for China.

2.2.5. Emission Factors

[19] An emission factor is defined as the amount of a compound released per amount of dry fuel consumed, expressed in units of g kg^{-1} [*Andreae and Merlet*, 2001]. It is variable due to intrafire variability and interfire variability [*Hegg et al.*, 1990]. Intrafire variability is mainly attributed to the burning dynamics (e.g., flaming and smoldering) during a fire, while interfire variability is mainly due to the differences of fuels' properties (e.g., elemental composition, moisture content, and size of components), local meteorological conditions, and local topography [*Hegg et al.*, 1990; *Ward*, 1990]. The emission factors of various trace gases are usually derived from field experiments in different forest types [*Cofer et al.*, 1988, 1989, 1990; *Hegg et al.*, 1990; *Delmas et al.*, 1991; *Kaufman et al.*, 1992; *Laursen et al.*, 1992] and they are usually an average with a floating value which is largely due to intrafire variability. In China, there are no existing experimental data to estimate the emission factors for each trace gas. Fortunately, some studies have partly proved that emission factors can be a function of forest type [*Cofer et al.*, 1990, 1992]. Therefore the method,

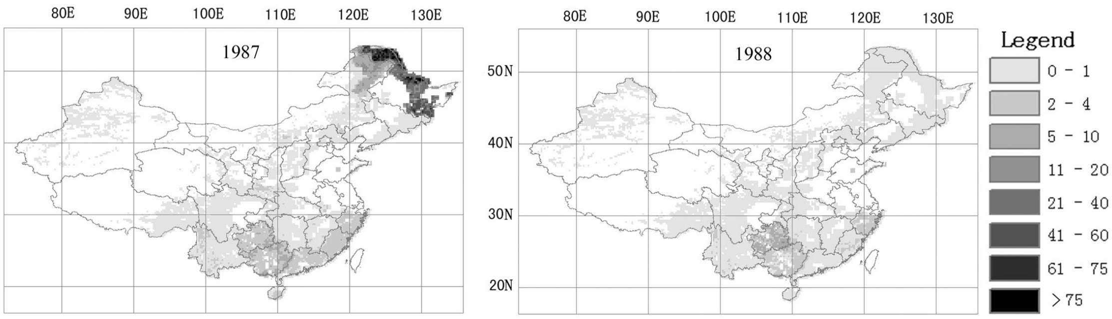

Figure 4. Fire-induced carbon emissions in the years of 1987 and 1988 (unit: Ton C).

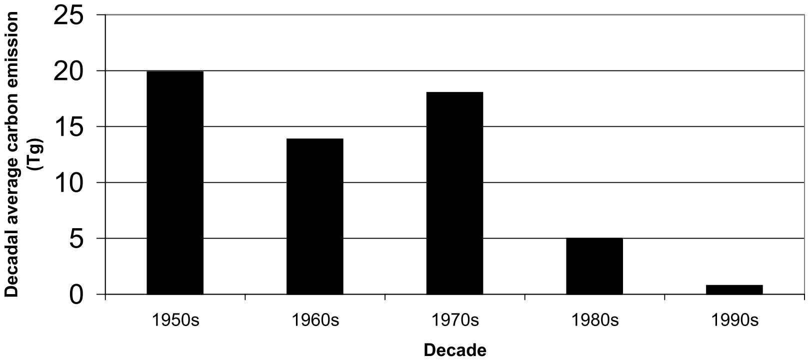

Figure 5. Decadal variation in fire-induced carbon emissions in China.

that for the large geographical area the emission factors of same forest type could be seen the same, has been adopted by many researchers [*Andreae and Merlet*, 2001; *Streets et al.*, 2003]. Also, we used the same methods applied in the estimation of combustion efficiency to deal with the emission factors for transitional forest types.

3. Result and Discussion

3.1. Spatiotemporal Variations in Forest Fire-Burned Area

[20] Fire regime is affected by both natural and anthropogenic factors which are variable temporally and geographically [*Liu*, 2004]. For the time period from 1950 to 2000, burned forest area varied from year to year (Figure 2). The highest annual burned area was in 1956 (2.798 million ha) and the lowest in 1993 (0.026 million ha). Most importantly, the contrast of the annual variations of the burned area in the pre-1980 was sharper than that in the post-1980. This temporal pattern of the burned area is primarily due to the application of fire suppression in China. Before 1980, substantial year-to-year variation in the burned area represents the natural pattern of forest fire occurrences. Since 1981, forest fire suppression has been strengthened across forest areas of China following the implementation of many fire suppression-related policies and laws [*State Forestry Administration*, 1989]. Within the period of post-1980, however, there is an abrupt increase in 1987 because of the large fires in the forest area of North China including the famous “Black Dragon” fire in that year that burned an estimate of 10 million ha [*Wang et al.*, 1996].

[21] The spatial method introduced above was used to obtain the grid-level fire data. Figure 2a shows the spatial pattern of the multiyear averages of burned area. The northeast and the southwest have the highest burned areas. For the northeast, the local dry and cold weather led to comparatively higher ignition probability [*Campbell and Flannigan*, 2000; *Cahoon et al.*, 1994] and more fuel accumulation than other regions. As a result, the burned area and the fire-related emissions discussed below are correspondingly higher. The large area burnt in the southwest is partially because of the slash-and-burn farming in the tropical and subtropical areas of this region.

3.2. Interannual and Decadal Variations in Forest Fire-Induced Carbon Emission

[22] Our study shows that from 1950 to 2000, the mean annual carbon release from forest fires in China was 11.31 Tg C, with a range of 8.55 Tg C to 13.9 Tg C. According to our TEM simulations, the mean annual net primary productivity (NPP) of Chinese forests for the same period was about 769.38 Tg C yr^{-1}. This implies that about 1.4% of NPP was returned to the atmosphere via biomass burning every year. Using equation (3), the total annual carbon released has been converted to the carbon-containing trace gases, respectively. The ranges of annual fire-induced emissions from 1950 to 2000 (and their averages) are as follows: 29.21 Tg to 47.53 Tg (40.66 Tg) CO_2, 1.48 Tg to 4.30 Tg (2.71 Tg) CO, 0.06 Tg to 0.2 Tg (0.112 Tg) CH_4, 0.05 Tg to 0.19 Tg (0.113 Tg) NMHC. It has been shown that the annual variations in fire-induced emission were more obvious before 1980, while from then to 2000, the annual fire-induced emissions became relatively low and stable, excepting the year of 1987 (Figures 2b, 3, and 4).

[23] Our analysis also shows substantial decadal variation in fire-induced carbon emission in China (Figure 5 and Table 3). Because of the increasing effort in fire suppression since the establishment of P. R. China, the decadal average carbon emissions were decreased from 1950s to 1990, excepting in 1970s. For 1970s, less devotion in fire for the period of the Cultural Revolution resulted in the sharp increase in fire-related emissions. However, the pattern of decadal variation differs from region to region (Figure 6). For example, northeast showed large carbon emission in the 1980s, but other regions appeared to be small emissions for the same time period.

[24] Figure 7 reflects the tendency of the average burned area per fire for each year of the study period. It can be seen that the burned area after 1980 was decreased dramatically. This is similar to the variations tendency of both the burned area and its corresponding fire-induced emissions. These could be partly explained by the anthropogenic impacts. Fire suppression is one of the powerful carbon management means. It could directly affect carbon emissions by reducing fire igniting agents, lessening fire severity and decreasing

Table 3. Decadal Emissions of CO_2, CO, CH_4, and NMHC From Forest Fires in China, Tg

	CO_2	CO	CH_4	NMHC
1950–1959	71.53	4.89	0.21	0.19
1960–1969	49.66	3.27	0.16	0.16
1970–1979	65.12	4.39	0.19	0.17
1980–1989	17.98	1.21	0.05	0.05
1990–1999	2.54	0.17	0.01	0.01

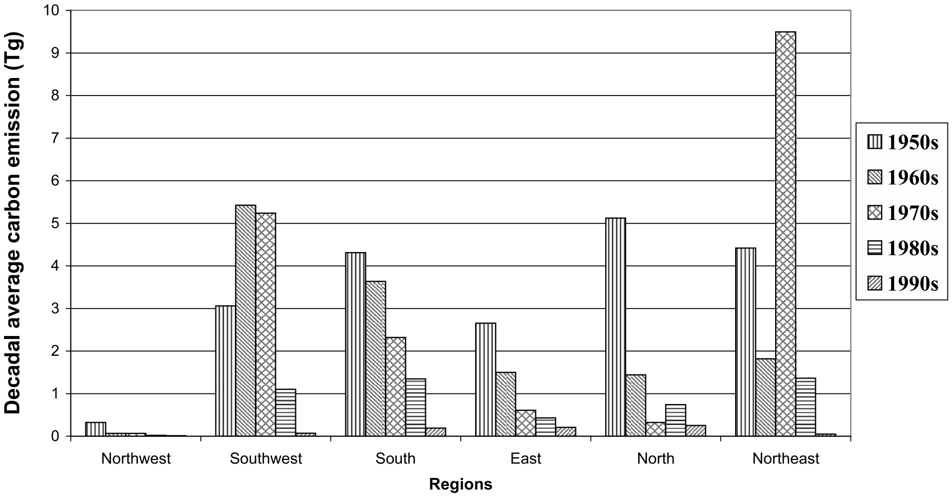

Figure 6. Decadal average carbon emissions for six sub-regions in China.

burned area [*Kasischke*, 2000b; *Ward and Mawdsley*, 2000]. China's more and more fiscal devotion to fire suppression after 1980 support the explanation very well.

3.3. Spatial Variability of Forest Fires-Induced Carbon Emission

[25] The climate, fuels, topography, and fire management practices differ spatially, which results in spatial variations in the burned area and hence the fire-related emissions across China. To analyze these regional variations in fire-induced carbon emission, we sum up the grid-level emissions by six regions and generate the regional distribution of fire-related emissions.

[26] Table 4 shows the multiyear averages of total carbon and each fire-induced emisions for China by regions. Not only for total carbon but also for the related other trace gases, the northeast is the highest among the six regions (Table 4 and Figure 8). From 1950 to 2000, 30% of the fire-induced carbon emissions in China had been released from the northeast where there is 21.4% (based on *FRSC* [1994]) of Chinese forest area and 28.98% [*Wang et al.*, 2001b] of Chinese forest carbon stocks, while only 0.01% released from the northwest. Also, the frequency of fire in the northeast is highest, 548.47 times per year. The huge carbon stock and high frequency of fire in the region make it the highest fire-induced emission part of the country.

[27] However, the spatial pattern of fire-induced carbon emission varied from decade to decade (Figure 9). During 1950s and 1970s, both northeast and southwest show large carbon release from forest fires. In the 1960s, the southwest region appeared to be more carbon emissions than others regions. This is mainly due to the large slash-and-burn practices which convert forest into agricultural lands during 3 years' calamities [*Ge et al.*, 2000]. In the recent two decades of 1980s and 1990s, however, fire-induced carbon emission remained relatively small and even distributed across the forest areas of the nation.

3.4. Comparison of Results and Methods in Fire Emission Estimations

[28] Our national level estimates on carbon and carbon-containing trace gases are comparable to another study [*Wang et al.*, 1996]. Using the same fire data, *Wang et al.* [1996] have estimated fire emissions in China for the time period from 1950 to 1992. They did not use the georeferenced method to estimate the biomass data but based it on

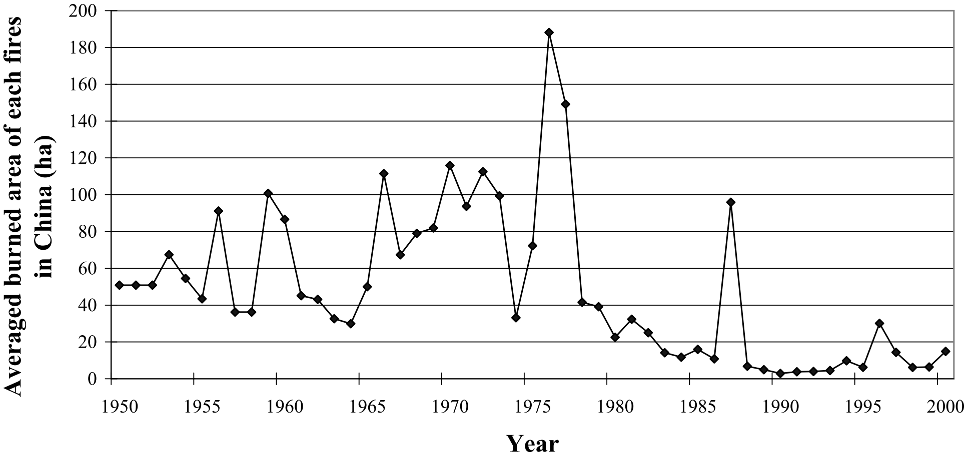

Figure 7. Mean burned area per fire for each year (1950–2000).

Table 4. Mean Annual Emissions of Trace Gases From Forest Fires in the Six Subregions of China (1950–2000)

	Annual Mean of the Fire-Induced Emissions, Tg yr^{-1}				
Regions	Total Carbon	CO_2	CO	CH_4	NMHC
Northwest	0.095 (0.078–0.110)	0.34 (0.26–0.38)	0.02 (0.01–0.03)	0.001 (0.0006–0.002)	0.001 (0.0005–0.002)
Southwest	2.92 (2.300–3.520)	10.38 (7.70–10.97)	0.67 (0.39–1.01)	0.038 (0.02–0.06)	0.041 (0.02–0.068)
South	2.32 (1.830–2.780)	8.28 (6.17–9.12)	0.53 (0.3–0.8)	0.029 (0.015–0.046)	0.03 (0.015–0.05)
East	1.06 (0.830–1.290)	3.77 (2.79–3.69)	0.24 (0.14–0.38)	0.014 (0.007–0.022)	0.015 (0.007–0.025)
North	1.55 (1.050–2.010)	5.61 (3.67–7.47)	0.42 (0.21–0.68)	0.013 (0.006–0.022)	0.0083 (0.003–0.015)
Northeast	3.36 (2.46–4.20)	12.28 (8.62–15.91)	0.86 (0.43–1.4)	0.028 (0.013–0.047)	0.018 (0.008–0.03)

the forest-volume stock inventory data. Also they did not analyze the annual fire emissions at grid level but calculated the multiyear mean at provincial level. Our estimate of annual carbon emission from forest fires in China for the time period from 1950 to 1992 is higher than that of *Wang et al.*'s [1996] (Table 5). Wang et al's estimate of CO emission is higher than our estimate partly because of the higher CO emission factor they used.

4. Conclusions and Needs for Future Research

[29] Combining the georeferenced forest cover data and the provincial fire inventory data with a process-based ecosystem model, we have estimated the fire-induced carbon emissions and specific trace gases in China from 1950 to 2000. Our results suggest that mean annual carbon emission from forest fires in China is about 11.31 Tg per year, varying from 8.55 to 13.9 Tg per year. This amount of carbon are converted to atmospheric emissions of trace gases as follows: (1) 40.66 Tg CO_2 with a range from 29.21 to 47.53 Tg, (2) 2.71 Tg CO with a range from 1.48 to 4.30 Tg, (3) 0.112 Tg CH_4 with a range from 0.06 to 0.2 Tg, and (4) 0.113 Tg NMHC with a range from 0.05 to 0.19 Tg. The spatiotemporal variability of input data and parameters has been considered in this study. This study represents the first spatially explicit estimation of carbon emission from forest fires at the national level in China. Our results indicate that China's fire-induced emissions are highly variable spatiotemporally. The results are in grid format with high spatiotemporal resolution so that they can be easily combined with the grid-based ecosystem models to evaluate the impacts of fire on ecosystem over a long term.

[30] Uncertainty exists in our estimate of forest fire-induced carbon emission because of uncertainty in the estimation of burned area, biomass, and other fire parameters. Forest biomass predicted by TEM in this study is higher than that estimated by forest inventory-based estimation [*Fan et al.*, 1998; *Wang et al.*, 2001b; *Pan et al.*, 2004]. Forest inventory data are valuable resource in forest biomass estimation because they provide detailed information on stand age, total area, and total stem volume for each forest type with more reliability at the provincial level [*Fan et al.*, 1998]. However, its coarse spatial resolution (i.e., provincial level) is far from our study needs (grid level) and could not represent the spatiotemporal variability of biomass. Further analysis is needed to refine the Terrestrial Ecosystem Model to reduce uncertainty in biomass estimates across the nation of China. To accurately estimate carbon emission from forest fires, it is needed to more accurately represent fire effect on soil organic carbon storage [*Wang et al.*, 2003].

[31] The estimate is limited by the availability of the existed experimental data of the combustion efficiency and emission factor. Both of them in a given grid cell could be

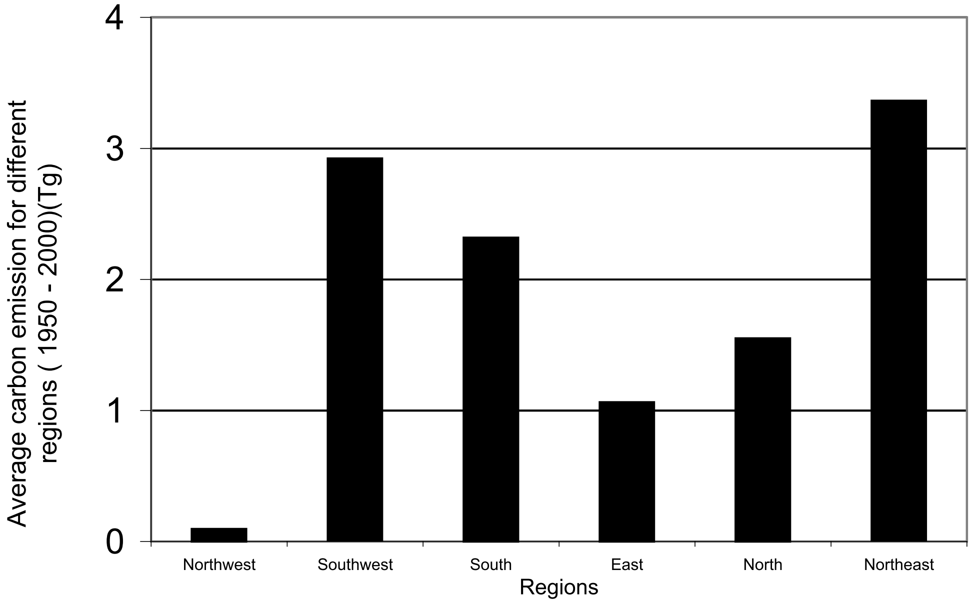

Figure 8. Mean carbon emissions for different regions induced by forest fires in China (1950–2000).

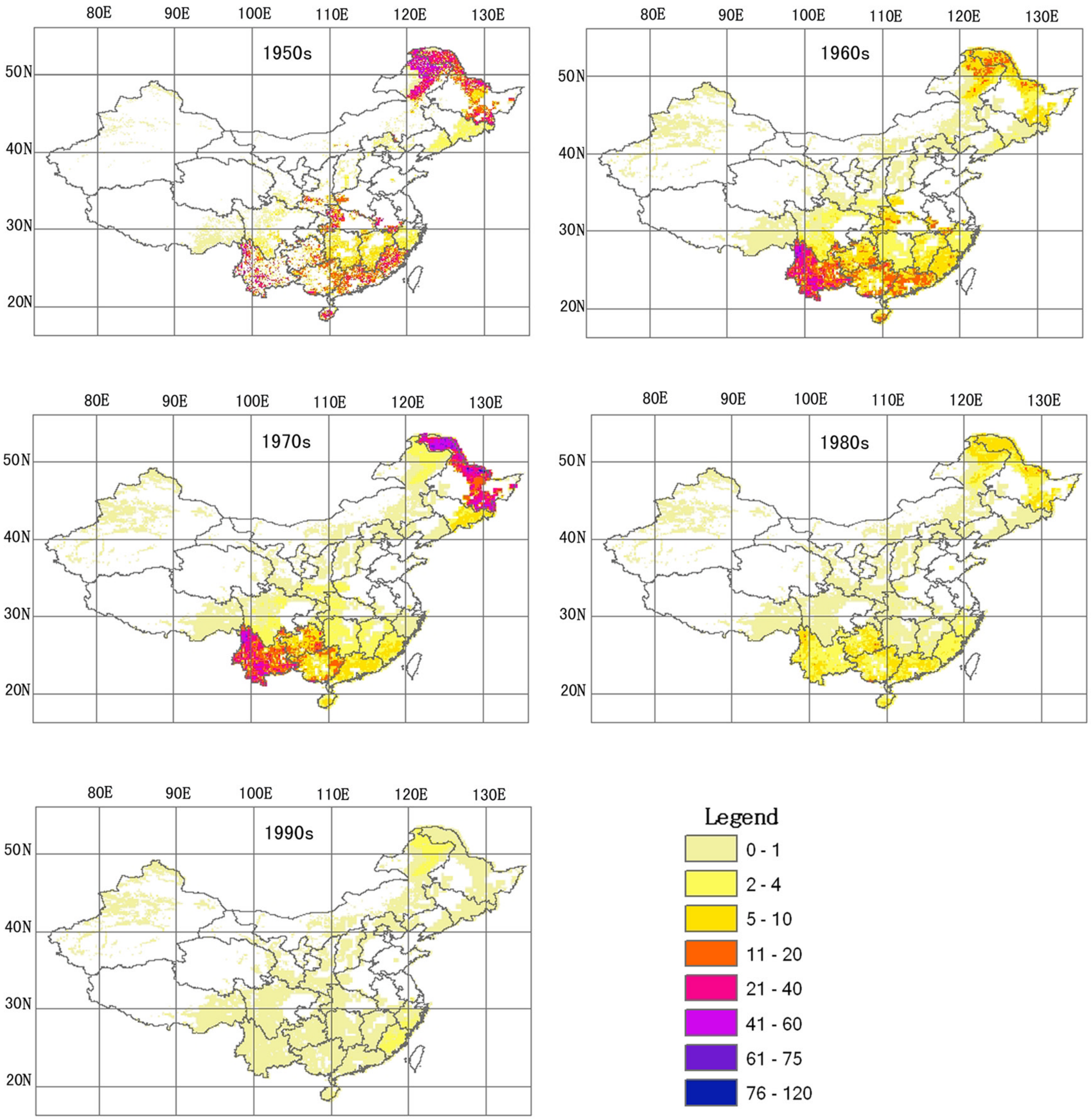

Figure 9. Decadal variations in carbon emission induced by forest fires across China (unit: Ton C).

influenced by many factors, such as forest type, intensity, and timing of fires, topography, wind, and tree stand age, etc. [*Cofer et al.*, 1989; *Hegg et al.*, 1990; *Ward*, 1990; *French et al.*, 2000; *Shvidenko and Nilsson*, 2000a; *Kasischke et al.*, 1995a; *Kasischke and Bruhwiler*, 2003]. It is impossible to account for all of these factors over a large geographical area, especially in China, where there are almost all forest types in the Northern Hemisphere and no any field experiments on fire-related parameters estimation. It is of critical important to have field experiments to test the generality of fire-related parameters across China in the future research.

[32] The estimate is to some extent limited by the availability of the higher-resolution spatiotemporal data. The coarser-resolution satellite remote sensing (RS) systems, such as System Probatoire pour l'Observation de la Terre (SPOT) vegetation, Advanced Very High Resolution Radiation (AVHRR), and Moderate Resolution Imaging Spectroradiometer (MODIS), could provide us more refined spatial fire-related data including fire location, burned area, fire severity, fuel load, combustion efficiency, and emission factor, etc. [*Patterson and Yool*, 1998; *Fraser et al.*, 2000; *Li et al.*, 2003; *Palacios-Orueta et al.*, 2004]. So along with the improvement of the fire detection algorithms, data processing, and noise reducing, introducing the remote sensing data into the fire disturbance research could facilitate it substantially and make it more accurate.

[33] Fire disturbance could affect the carbon cycle not only through carbon emission but also through the carbon releasing/sequestrating processes after fires. The latter is believed to be more crucial over a long term. As so far, much attention has been paid to the biomass burning, while carbon dynamics after fire disturbance is still in debate and the related studies are still mainly focused on the small-scale influences of fire on the biogeochemical properties of

Table 5. Comparison of Fire-Related Emission Estimates Between *Wang et al.* [1996, 2001a] and Our Result for the Period From 1950 to 1992, Tg[a]

Emissions	Our Result (1950–1992)	*Wang et al.* [1996, 2001a]
C	13.24(10.02∼16.28)	11.30
CO_2	47.61(34.21∼55.66)	32.85
CO	3.21(1.73∼5.03)	6.30
CH_4	0.14(0.07∼0.23)	0.15
NMHC	0.13(0.06∼0.22)	N/A

[a] Here N/A is no data.

ecosystem as well as on vegetation metabolism based on field experiments [*Richter et al.*, 2000; *Andersson et al.*, 2004; *Neary et al.*, 1999; *Amiro et al.*, 1999; *Wiseman and Seiler*, 2004].

[34] It is widely believed that climate warming will be accompanied by the increased fire frequency, burned area, burn severity, and the duration of the fire season. Consequently, the large-scale influence of fire on the carbon cycle should be paid more attention. Therefore it is crucial to incorporate fire disturbance into regional carbon dynamics by combining field studies with the large-scale ecosystem models which can simulate the interaction of the components of ecosystem on a large scale. Clearly, the integration of field experiment, remote sensing, and modeling will be essential to facilitate further exploration of large-scale carbon dynamics with respect to fire disturbance.

[35] **Acknowledgments.** This work has been supported by NASA Interdisciplinary Science Program (NNG04GM39C), China's Ministry of Science and Technology (MOST) 973 Program (2002CB412500), Chinese Academy of Sciences ODS Program, and NSFC International Cooperative Program (40128005). We thank three anonymous reviewers for very helpful comments and suggestions.

References

Amiro, B. D., J. I. MacPherson, and R. L. Desjardins (1999), BOREAS flight measurements of forest-fire effects on carbon dioxide and energy fluxes, *Agric. For. Meteorol.*, *96*, 199–208.

Andersson, M., A. Michelsen, M. Jensen, and A. Kjøller (2004), Tropical savannah woodland: Effects of experimental fire on soil microorganisms and soil emissions of carbon dioxide, *Soil Biol. Biochem.*, *36*, 849–858.

Andreae, M. O., and P. Merlet (2001), Emission of trace gases and aerosols from biomass burning, *Global Biogeochem. Cycles*, *15*, 955–966.

Aulair, A. N. D., and T. B. Carter (1993), Forest wildfires as a recent source of CO_2 at northern latitudes, *Can. J. For. Res.*, *23*, 1528–1536.

Brown, S., J. Sathaye, M. Cannell, and P. E. Kauppi (1996), Management of forests for mitigation of greenhouse gas emissions, in *Climate Change 1995—Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses*, edited by R. T. Watson et al., pp. 773–797, Cambridge Univ. Press, New York.

Cahoon, D. R., Jr., B. J. Stocks, J. S. Levine, W. R. Cofer III, and J. M. Pierson (1994), Satellite analysis of the severe 1987 forest fires in northern China and southeastern Siberia, *J. Geophys. Res.*, *99*, 18,627–18,638.

Campbell, I. D., and M. D. Flannigan (2000), Long-term perspectives on fire-climate-vegetation relationships in the North American boreal forest, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 151–172, Springer, New York.

Chuvieco, E., D. Cocero, I. Aguado, A. Palacios, and E. Prado (2004), Improving burning efficiency estimates through satellite assessment of fuel moisture content, *J. Geophys. Res.*, *109*, D14S07, doi:10.1029/2003JD003467.

Cofer, W. R., III, S. J. Levine, P. J. Riggan, D. I. Sebacher, E. L. Winstead, E. F. Shaw Jr., J. A. Brass, and V. G. Amerosia (1988), Trace gas emissions from a Mid-latitude prescribed chaparral fire, *J. Geophys. Res.*, *93*, 1653–1658.

Cofer, W. R., III, S. J. Levine, D. I. Sebacher, E. L. Winstead, P. J. Riggan, B. J. Stocks, J. A. Brass, V. G. Ambrosia, and A. J. Boston (1989), Trace gas emissions from chaparral and boreal forest fires, *J. Geophys. Res.*, *94*, 2255–2259.

Cofer, W. R., III, S. J. Levine, E. L. Winstead, and B. J. Stock (1990), Gaseous emissioins from Canadian boreal forest fires, *Atmos. Environ.*, *24A*, 1653–1659.

Cofer, W. R., III., E. L. Winstead, B. J. Stocks, L. W. Overbay, J. G. Goldammer, D. R. Cahoon, and J. S. Levin (1996), Emissions from boreal forest fires: Are the atmospheric chemical impacts underestimated?, in *Biomass Burning and Global Change*, vol. II, edited by J. S. Levine, pp. 834–839, MIT Press, Cambridge, Mass.

Conard, S. G., and G. A. lvanova (1997), Wildfire in Russian boreal forests-potential impacts of fire regime characteristics on emissions and global carbon balance estimates, *Environ. Pollut.*, *98*(3), 305–313.

Conard, S. G., A. I. Sukhinin, B. J. Stocks, D. R. Cahoon, E. P. Davidenko, and G. A. Ivanova (2002), Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia, *Clim. Change*, *55*, 197–211.

Crutzen, P. J., and M. O. Andreae (1990), Biomass burning in the tropics: impact on the atmospheric chemistry and biogeochemical cycles, *Science*, *250*, 1669–1678.

Cruzten, P. J., L. E. Heidt, J. P. Krasnec, W. H. Pollock, and W. Seiler (1979), Biomass burning as a source of the atmospheric gases CO, H_2,N_2O,NO,CH_3Cl, and COS, *Nature*, *282*, 253–256.

Delmas, R. A., A. Marenco, J. P. Tathy, B. Cros, and J. G. R. Baudet (1991), Sources and sinks of methane in the African savanna CH_4 emissions from biomass burning, *J. Geophys. Res.*, *96*, 7287–7299.

Dixon, R. K., S. Brown, R. A. Houghton, A. M. Solomon, M. C. Trexler, and J. Wisniewski (1994), Carbon pools and flux of global forest ecosystems, *Science*, *262*, 185–190.

Fan, S., M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans (1998), A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models, *Science*, *282*, 442–446.

Fearnside, P. M., N. Leal Jr., and F. M. Fernandes (1993), Rainforest burning and the global can budget: Biomass, combustion efficiency, and charcoal formation in the Brazilian Amazon, *J. Geophys. Res.*, *98*, 16,733–16,743.

Fraser, R. H., and Z. Li (2002), Estimating fire-related parameters in boreal forest using SPOT VEGETATION, *Remote Sens. Environ.*, *82*, 95–110.

Fraser, R. H., Z. Li, and J. Cihlar (2000), Hotspot and NDVI differencing synergy (HANDS): A new technique for burned area mapping over boreal forest, *Remote Sens. Environ.*, *74*, 362–376.

French, N. H. F., E. S. Kasischke, B. J. Stock, J. P. Mudd, D. L. Martell, and B. S. Lee (2000), Carbon released from fires in North American boreal forests, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 377–388, Springer, New York.

FRSC (1994), *Forest Resource Statistics of China (1989–1993)*, China's For. Press, Beijing, China.

Ge, Q., M. Zhao, and J. Zheng (2000), Land use change of China during the 20th century, *Acta Geograp. Sinica*, *55*(6), 698–706.

Hegg, D. A., L. F. Radke, and P. V. Hobbs (1990), Emissions of some trace gases from biomass fires, *J. Geophys. Res.*, *95*, 5669–5675.

Heilig, G. K. (1999), Can China feed itself: A system for evaluation of policy options, Int. Inst. for Appl. Syst. Anal., Laxenburg, Austria. (Available at http://www.iiasa.ac.at/Research/LUC/ChinaFood/index_m.htm)

Hicke, J. A., G. P. Asner, E. S. Kasischke, H. F. C. French, J. T. Randerson, G. J. Collatz, B. J. Stock, C. J. Tucker, S. O. Los, and C. B. Field (2003), Postfire response of North American boreal forest net primary productivity analyzed with satellite observations, *Global Change Biol.*, *9*, 1145–1157.

Hou, X. (1979), *Vegetation Map of the People's Republic of China*, (1:4,000,000), Chinese Map Press, Beijing.

Houghton, R. A., and J. L. Hackler (2003), Sources and sinks of carbon from land-use change in China, *Global Biogeochem. Cycles*, *17*(2), 1034, doi:10.1029/2002GB001970.

Kasischke, E. S. (2000a), Processes influencing carbon cycling in the north American boreal forest, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 104–110, Springer, New York.

Kasischke, E. S. (2000b), Boreal ecosystem in the global cycle, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 19–30, Springer, New York.

Kasischke, E. S., and L. P. Bruhwiler (2003), Emissions of carbon dioxide, carbon monoxide, and methane from boreal forest fires in 1998, *J. Geophys. Res.*, *108*(D1), 8146, doi:10.1029/2001JD000461.

Kasischke, E. S., and N. H. F. French (1997), Constraints on using AVHRR composite index imagery to study patterns of vegetation cover in boreal forests, *Int. J. Remote Sens.*, *18*, 2403–2426.

Kasischke, E. S., N. H. F. French, L. L. Bourgeau-Chavez, and N. L. Christensen (1995a), Estimating release of carbon from 1990 and 1991 forest fires in Alaska, *J. Geophys. Res*, *100*, 2941–2951.

Kasischke, E. S., N. L. Christensen, and B. J. Stocks (1995b), Fire, global warming, and the carbon balance of boreal forests, *Eco. Appl.*, *5*, 437–451.

Kasischke, E. S, B. J. Stocks, K. O'Neill, N. H. F. French, and L. L. Bourgeau-Chavez (2000), Direct effects of fire on the boreal forest carbon budget, in *Biomass Burning and its Interrelationships With the Climate System*, edited by J. L. Innes, M. Benistion, and M. Verstraete, pp. 51–68, Springer, New York.

Kaufman, Y. J., A. Setzer, D. Ward, D. Tanre, B. N. Holben, P. Menzel, M. C. Pereira, and R. Rasmussen (1992), Biomass burning airborn and spaceborne experiment in the Amazons (BASE-A), *J. Geophys. Res.*, *97*, 14,581–14,599.

Klepper, B. (1991), Root-shoot relationships, in *Plant Roots: The Hidden Half*, edited by Y. Waisel, A. Eshel, and U. Kafkafi, pp. 265–286, Marcel Dekker, New York.

Korontzi, S., C. O. Justice, and R. J. Scholes (2003), Influence of timing and spatial extent of savanna fires in southern Africa on atmospheric emissions, *J. Arid Environ.*, *54*, 395–404.

Kurz, W. A., and M. J. Apps (1999), A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector, *Ecol. Appl.*, *9*, 526–547.

Langenfelds, R. L., R. J. Francey, B. C. Pak, L. P. Steele, S. J. Lioyd, C. M. Trudinger, and C. E. Allison (2002), Interannual growth rate variations of atmospheric CO2 and its $\delta\ ^{13}$C,H_2, CH_4, and CO between 1992 and 1999 linked to biomass burning, *Global Biogeochem. Cycles*, *16*(3), 1048, doi:10.1029/2001GB001466.

Laursen, K. K., P. V. Hobbs, and L. F. Radke (1992), Some trace gas emissions from North American biomass fires with an assessment of regional and global fluxes from biomass burning, *J. Geophys. Res.*, *97*, 20,687–20,701.

Levine, J. S., and W. R. Cofer III (2000), Boreal forest fire emissions and the chemistry of the atmosphere, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 31–48, Springer, New York.

Li, W., and F. Li (1996), *Research of Forest Resources in China*, China Forest Publ., Beijing, China.

Li, X. (1999), Change of arable land area in China during the past 20 years and its policy implications (in Chinese), *J. Natural Res.*, *4*, 329–333.

Li, Z., R. Fraser, J. Jin, A. A. Abuelgasim, I. Csiszar, P. Gong, R. Pu, and W. Hao (2003), Evaluation of satellite-based algorithms for fire detection and mapping within North America, *J. Geophys. Res.*, *108*(D2), 4076, doi:10.1029/2001JD001377.

Liu, J. Y., H. Tian, M. Liu, D. Zhuang, J. M. Melillo, and Z. Zhuang (2005), China's Changing Landscape During the 1990s: Large-scale land transformations estimated with satellite data, *Geophys. Res. Lett.*, *32*, L02405, doi:10.1029/2004GL021649.

Liu, Y. Q. (2004), Variability of wildland fire emissions across the continuous United States, *Atmos. Environ.*, *38*, 3489–3499.

Lü, A., H. Tian, and Y. Liu (2005), State-of-the-art in quantifying fire disturbance and ecosystem carbon cycle (in Chinese), *Acta Ecol. Sinica*, *25*, 2734–2743.

McGuire, A. D., et al. (2001), Carbon balance of the terrestrial biosphere in the twentieth century: Analyses of CO2, climate and land-use effects with four process-based ecosystem models, *Global Biogeochem. Cycles*, *15*, 183–206.

Melillo, J. M., A. D. McGuire, D. W. Kicklighter, B. Moore III, C. Vorosmarty, and A. Schloss (1993), Global climate change and terrestrial net primary production, *Nature*, *363*, 234–240.

Morrissey, L. A., G. P. Livingston, and S. C. Zoltai (2000), Influences of fire and climate change on patterns of carbon emissions in boreal peatlands, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 423–439, Springer, New York.

Neary, D. G., C. C. Klopatek, L. F. DeBano, and P. F. Ffolliott (1999), Fire effects on belowground sustainability: A review and synthesis, *For. Ecol. Manag.*, *122*, 51–71.

O'Neill, K. P., E. S. Kasischke, and D. D. Richter (2003), Seasonal and decadal patterns of soil carbon uptake and emission along an age sequence of burned black spruce stands in interior Alaska, *J. Geophys. Res.*, *108*(D1), 8155, doi:10.1029/2001JD000443.

Palacios-Orueta, A., A. Parra, E. Chuvieco, and C. Carmona-Moreno (2004), Remote Sensing and geographic information systems methods for global spatiotemporal modeling of biomass burning emissions: Assessment in the African continent, *J. Geophys. Res.*, *109*, D14S09, doi:10.1029/2004JD004734.

Pan, Y., T. Luo, R. Birdsey, J. Hom, and J. M. Melillo (2004), New estimates of carbon storage and sequestration in China's forest: Effects of age-class and method on inventory-based carbon estimates, *Climate Change*, *67*, 211–236.

Patterson, M. W., and S. R. Yool (1998), Mapping fire-induced vegetation mortality using Landsat Thematic Mapper data: A comparison of linear transformation techniques, *Remote Sens. Environ.*, *65*, 132–142.

Peng, C. H., and M. J. Apps (1999), Modeling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes, *Ecol. Model.*, *122*, 175–193.

Pickett, S. T. A., and P. S. White (1985), *The Ecology of Natural Disturbance and Patch Dynamics*, Elsevier, New York.

Richter, D. D., K. P. O'Neil, and E. S. Kasischke (2000), Postfire stimulation of microbial decomposition in black spruce (Picea mariana L.) forest soils: A hypothesis, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp.197–213, Springer, New York.

Schimel, D., and D. Baker (2002), The wildfire factor, *Nature*, *420*, 29–30.

Schimel, D., et al. (2000), Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States, *Science*, *287*, 2004–2006.

Scholes, R. J., J. Kendall, and C. O. Justice (1996), The quantity of biomass burned in southern Africa, *J. Geophys. Res.*, *101*, 23,667–23,676.

Seiler, W., and P. J. Crutzen (1980), Estimates of gross and net fluxes of carbon between the biosphere and the atmophere from biomass burning, *Climate Change*, *2*, 207–247.

Shvidenko, A. Z., and S. Nilsson (2000a), Extent, distributioin, and ecological role of fire in Russia forests, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 132–150, Springer, New York.

Shvidenko, A. Z., and S. Nilsson (2000b), Fire and the carbon budget of Russia forests, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E. S. Kasischke and B. J. Stocks, pp. 290–311, Springer, New York.

State Administration of Forestry (1989), *Forestry Data Compilation (1949–1987)*, China's For. Press, Beijing.

State Administration of Forestry (2000), *Forestry Development in China (1949–1999)*, pp.185–188, China's For. Press, Beijing China.

Stocks, B. J., M. A. Fosberg, M. B. Wotton, T. J. Lynham, and K. C. Ryan (2000), Climate change and forest fire activity in North American boreal forests, in *Fire, Climate Change and Carbon Cycling in North American Boreal Forests, Ecol. Stud. Ser.*, edited by E S Kasischke and B. J. Stocks, pp. 368–376, Springer, New York.

Streets, D. G., et al. (2003), An inventory of gaseous and primary aerosol emissions in Asia in the year 2000, *J. Geophys. Res.*, *108*(D21), 8809, doi:10.1029/2002JD003093.

Swetnam, T. W. (1993), Fire history and climate change in giant Sequoia groves, *Science*, *262*, 885–889.

Tian, H., J. M. Melillo, D. W. Kicklighter, A. D. McGuire, J. Helfrich, B. Moore III, and C.J. Vörösmarty (1998), Effect of interannual climate variability on carbon storage in Amazonian ecosystems, *Nature*, *396*, 664–667.

Tian, H. Q., J. M. Melillo, D. W. Kicklighter, S. Pan, J. Liu, A. D. McGuire, and B. Moore III (2003), Regional carbon dynamics in monsoon Asia and its implications to the global carbon cycle, *Global Planet. Change*, *37*, 201–217.

Tian, H. Q., J. Liu, J. Melillo, M. Liu, D. Kicklighter, X. Yan and S. Pan (2005), The Terrestrial Carbon Budget in East Asia: Human and Natural Impacts, in *Changes in the Human-Monsoon System of East Asia in the Context of Global Change*, edited by C. Fu, J. Freney, and J. Stewart, Island Press, Washington, D. C., in press.

van der Werf, G. R., J. T. Randerson, G. J. Collatz, L. Giglio, P. S. Kasibhatla, A. F. Arellano Jr., S. C. Olsen, and E. S. Kasischke (2004), Continental-scale partitioning of fire emissions during the 1997 to 2001 El Niño/La Niña period, *Science*, *303*, 73–76.

Wang, S., H. Tian, J. Liu, and S. Pan (2003), Pattern and change of soil organic carbon storage in China: 1960s–1980s, *Tellus, Ser. B*, *55*, 416–427.

Wang, X., Z. Feng, and Y. Zhuang (1996), Forest fires in China: carbon dioxide emissions to the atmosphere, in *Biomass Burning and Climate Change*, edited by J. S. Levine, pp. 771–779, MIT Press, Cambridge, Mass.

Wang, X., Z. Feng, and Y. Zhuang (2001a), CO2,CO and CH4 emissions from forest fires in China, *Sci. Silvae Sinicae*, *37*(1), 90–95.

Wang, X., Z. Feng, and Z. Ouyang (2001b), The impact of human disturbance on vegetative carbon storage in forest ecosystems in China, *For. Ecol. Manage.*, *148*, 117–123.

Ward, D. E. (1990), Factors influencing the emissions of gases and particulate matter from biomass burning, in *Fire in the Tropical Biota: Ecosystem Processes and Global Challenges*, edited by J. G. Goldammer, pp. 418–436, Springer, New York.

Ward, P. C., and W. Mawdsley (2000), Fire management in the boreal forests of Canada, in *Fire, Climate Change, and Carbon Cycling in the Boreal Forest*, edited by E. S. Kasischke and B. J. Stocks, pp. 66–84, Springer, New York.

Wardle, D. A., G. Hornberg, O. Zackrisson, M. Kalela-Brundin, and D. A. Coomes (2003), Long-term effects of wildfire on ecosystem properties across an island area gradient, *Science*, *300*, 972–975.

Wiseman, P. E., and J. R. Seiler (2004), Soil CO_2 efflux across four age classes of plantation loblolly pine (*Pinus taeda L.*) on the Virginia Piedmont, *For. Ecol. Manage.*, *192*, 297–311.

Wong, C. S. (1978), Atmospheric input of carbon dioxide from burning wood, *Science*, *200*, 197–200.

Wotawa, C., and M. Trainer (2000), The influence of Canadian forest fires on pollutant concentrations in the United States, *Science*, *288*, 324–328.

Wu, C., and H. Guo (1994), *Land Use of China* (in Chinese), Beijing Sci. Press, Beijing, China.

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