Global carbon emissions from biomass burning in the 20th century

Florent Mouillot,[1,2] Ajay Narasimha,[1] Yves Balkanski,[3] Jean-François Lamarque,[4] and Christopher B. Field[1]

Received 23 September 2005; revised 9 November 2005; accepted 21 November 2005; published 4 January 2006.

[1] We used a new, 100-year, $1 \times 1°$ global fire map and a carbon cycle model (CASA) to provide a yearly gridded estimate of the temporal trend in carbon emissions due to wildfires through the 20th century. 2700–3325 Tg C y^{-1} burn at the end of the 20th century, compared to 1500–2700 Tg C y^{-1} at the beginning, with increasing uncertainty moving backward in time. There have been major changes in the regional distribution of emissions from fires, as a consequence of i) increased burning in tropical savannas and ii) a switch of emissions from temperate and boreal forests towards the tropics. The frequently-used assumption that pre-industrial emissions were 10% of present biomass burning is clearly inadequate, in terms of both the total amount and the spatial distribution of combustion.
Citation: Mouillot, F., A. Narasimha, Y. Balkanski, J.-F. Lamarque, and C. B. Field (2006), Global carbon emissions from biomass burning in the 20th century, *Geophys. Res. Lett.*, *33*, L01801, doi:10.1029/2005GL024707.

1. Introduction

[2] The total amount of carbon emitted to the atmosphere from biomass burning is uncertain. Neither combustion efficiencies nor the extent of burned areas is known with precision [*Kasischke and Penner*, 2004]. Even recent global studies based on remote sensing provide a range of estimates varying in their amount and spatial distribution [*Boschetti et al.*, 2004]. However, these cluster around the conclusion that approximately 600 Mha burn annually, emitting around 2500 Tg C y^{-1} to the atmosphere [*Liousse et al.*, 2004]. Within this context, pre-industrial C emissions from biomass burning are even more difficult to estimate. One common assumption has been that pre-industrial emissions were 10% of the present amount, with the current spatial distribution [*Crutzen and Zimmermann*, 1991]. Some recent studies assume a less drastic increase through time [*Ito and Penner*, 2005; *Van Aardenne et al.*, 2001]. For this paper, we focused on developing an estimate of C emissions from biomass burning for the 1980's/1990's, building on results of recent studies, and on extending that to a 100-year history. We computed the direct emissions from biomass burning using the CASA model [*Potter et al.*, 1993] driven by a new gridded, global reconstruction of burned areas through the 20th century. This study, a first spatially-explicit global estimate of the temporal trend of carbon emissions due to fires over the last century, provides yearly maps of carbon emissions.

[1]Department of Global Ecology, Carnegie Institution of Washington, Stanford, California, USA.
[2]Now at IRD UR060/DREAM, CEFE-CNRS, Montpellier, France.
[3]Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France.
[4]Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, Colorado, USA.

0094-8276/06/2005GL024707

2. Carbon Emission Calculation

[3] The amount of carbon emitted directly to the atmosphere by fires (E) is given by

$$E = \Sigma S.C_i.B_i \tag{1}$$

where S is the burned area, C is the combustion efficiency and B the amount of available biomass of fuel types i (wood w, leaves l or litter lit).

[4] We calculated available fuel biomass on a yearly time step using the CASA biogeochemistry model [*Potter et al.*, 1993], driven by monthly climate (precipitation, temperature, solar radiation) and a vegetation index NDVI (Normalized Difference Vegetation Index) for a single year (1987). CASA calculates monthly NPP from f-APAR (fraction of Absorbed Photosynthetically Active Radiation) computed from NDVI, PAR (Photosynthetically Active Radiation), and an empirically determined light-use efficiency *Emax*, which is adjusted based on temperature and precipitation. We set *Emax* at 0.43 for all the biomes. Other studies use biome specific *Emax* for a better representation [*Still et al.*, 2004]. Adjusting *Emax* changes absolute values of NPP, but, when held constant over a simulation, has no effect on the relative temporal or spatial pattern. Parameters that determine the turnover times of carbon in living biomass, litter, and soil pools are constants for each of 12 global biomes, based on turnover values in the literature. We modified the *extraeff* decomposition parameter from 0.3 to 0.005 to increase carbon accumulation in the passive soil pool and improve agreement between the model and observations (Table 1). We used the biome map for current vegetation from *DeFries and Townshend* [1994], where we replaced the cultivated lands in the biome map with potential vegetation from the same study. Estimated biomass and soil carbon pools were compared with current databases and models (Table 1).

[5] We used a combustion procedure within the CASA model, in which carbon pools are updated yearly, as described by *Van der Werf et al.* [2003]. For forested biomes and biomes with a mix of forests and grasslands, a large proportion of the fires affect only the ground layer, leaving trees alive and unburned. For these biomes, we introduced a tree mortality parameter M (percentage of burned area in which trees are burned) resulting in the following emission equation:

$$E = S.C_l.B_l + S.C_{lit}.B_{lit} + S.C_w.B_w.M \tag{2}$$

[6] To account for effects of fire on soil carbon, we included combustion of the surface, slow, and passive soil

Table 1. Average Aboveground Biomass and Soil Carbon Stocks Simulated by CASA and Compared to the Current Knowledge of Global Carbon Stocks[a]

	Biomass (10^3 gC.m^{-2})		Soil (10^3 gC.m^{-2})		
	Observed	Simulated	Observed	Simulated	References
Boreal (North America)	3.2	3.0	9.4	10.4	1,2
Boreal (Russia)	3.8	4.8	16.0	13.5	1,2
Temperate (North Amercia)	5.1	6.0	6.0	8.6	1,2
Temperate (Europe)	3.9	4.0	7.8	7.5	1,2
Tropical forest (Africa)	9.5	15	5–20	8.3	2,4
Tropical forest (South America)	12–20	15	5–10	8.3	2,3,4
Savannas	1.2–2.5	1.75	3–10	5.8	2,4

[a]References are (1) *Goodale et al.* [2002], (2) *Krinner et al.* [2005], (3) *Houghton et al.* [2001], (4) *Van der Werf et al.* [2003].

carbon pools in the forested biomes (biome types 1–6) [*French et al.*, 2002; *Guild et al.*, 2004; *Soja et al.*, 2004]. We used 50%, 20% and 5% of the litter combustion efficiency C_{lit}, respectively, for the surface, slow and passive soil carbon pools. Combustion efficiencies and mortality rates, assumed to be constant through the century, are summarized in Table 2.

[7] As input for areas burned, we used the 1° × 1°, 100-year fire history of *Mouillot and Field* [2005], updated with recent data from *Kasischke et al.* [2005] and *Sukhinin et al.* [2004] for Russian fires in the 1990's. To acknowledge the low confidence in the dataset and in the changes in combustion efficiencies due to changes in fire types before the 1960's, we also used a lower scenario. For this, we successively subtracted 1% y^{-1} to the burned area, working backwards from 1960, leading to a −60% scenario for 1900. This sensitivity analysis provides a reference scale to evaluate the effect of uncertainty in both burned area and combustion efficiency at the beginning of the century. The lower estimate for burned area, −60% below our standard estimate for 1900, is not intended to represent a lower confidence limit in a strict sense. Instead it is an informal estimate of the possible uncertainty in burned area and combustion efficiency.

[8] We spun-up the model for 1000 years before starting the simulation. The fire regime during the spin-up was the average 1900–1910 fire regime. This period was probably representative of the fire regime in the 50 years before 1900. Even though burned areas before 1,850 may have been much smaller than those after 1850 in boreal and temperate forests [*Chen et al.* 2000], consequences of errors prior to 1850 have limited leverage on the simulated pools in 1900.

3. Results

[9] Total direct emission from fires was 3325 Tg C y^{-1} for the 1990's. Of this total, 1670 Tg C y^{-1} (50%) came from savannas, 1260 Tg C y^{-1} (38%) came from tropical forests, 209 Tg C y^{-1} (6.2%) came from boreal forests, and 186 Tg C y^{-1} (5.6%) came from temperate forests. The total estimate of biomass burning for the 1990's is slightly above the high end of published values (Table 3), though the estimate for many biomes is within the published range. The high values in our study are mainly for the tropics, for which the burned area in the database of *Mouillot and Field* [2005] was high compared to other studies [*Van der Werf et al.*, 2003; *Tansey et al.*, 2004]. In addition, we used climate data for 1987 only, a year favorable for savanna NPP. Simulations with a 40% decrease in savanna burned areas induced a 25% decrease in carbon emissions, a non-linear relationship due to fire feed-backs on available biomass (Figure 1, dotted lines).

[10] Starting from our estimates for the 1990s, we calculate that annual carbon emissions from biomass burning in 1900 were approximately 2750 Tg C y^{-1}, equivalent to 82% of present emissions (Figure 1). The minimum carbon fluxes occurred in the 1960's, when the total dropped to 2200 Tg C y^{-1}. With a rough estimate for the large uncertainties in burned area at the beginning of the century, the range of emissions based on a −60% lower limit was 1500 to 2750 Tg C y^{-1} in 1900. The largest contributor to the overall uncertainty is incomplete knowledge of the extent of savanna burning. However, the hypothesis that emissions from fires at the beginning of the century were only 10% of those at present [*Crutzen and Zimmerman*, 1991] is unlikely to be correct. Our estimates are closer to the 50% hypothesis [*Van Aardenne et al.*, 2001] used in more recent studies. In contrast to past estimates, our results based on the global fire history and biogeochemistry model indicate a trajectory of fire emissions that started and ended the 20th century at similar values (Figure 1). On a biome by biome basis (Figure 1), carbon emissions at the beginning of the century were 46–86% of the present value in savannas, 15–30% in tropical forests, 62–157% in boreal forests, and 269–359% in temperate forests. When focusing on conterminous USA, our estimate of 270–410 Tg C y^{-1} in 1900 is near the center of the 250–610 Pg C y^{-1} range found by *Leenhouts* [1998], despite the fact that combustion efficiencies should have been much lower at the beginning of the century, due to more frequent, lower-intensity surface fires.

Table 2. Combustion Efficiencies for Fuels Affected by Fires[a]

Biome Type	C_w	C_l	C_{cwd}	C_{lit}	M
1	0.3	0.9	0.9	0.9	0.1
2	0.5	0.9	0.5	0.7	0.5
3	0.5	0.8	0.5	0.9	0.2
4	0.3	0.8	0.5	0.8	0.9
5	0.3	0.8	0.4	0.4	0.36
6	0.5	0.75	0.01	0.2	0.03
7	0.5	0.75	0.01	0.2	0.001
8	0.6	0.9	0.6	0.9	0.9

[a]Subscripts indicate w: wood, l: leaves, lit: litter, cwd: coarse woody debris. M is the percentage of trees (wood biomass) affected by fires. Biome types are: (1) broad leaf evergreen trees, (2) broad leaf deciduous trees, (3) mixed trees, (4) needleleaf evergreen tress, (5) high latitude deciduous trees, (6) grass with 10–40% trees, (7) grass with >10% trees, (8) shrubs, (>8) no vegetation.

Table 3. Carbon Emissions From Fires (Tg C y^{-1}) in the 1990s[a]

	This Study	Previous Estimates	References
USA	67	35–85	1
Canada	43	35–64	2, 3, 9
S. America (savanna)	468	320–600	4, 5
S.America (tropical forest)	650	350–710	4, 5, 6
S.America (temperate forest)	5		n.a.
Africa (savanna)	1050	600–1300	4, 6, 7
Africa (tropical forest)	290	310	″
Europe	7		n.a.
S. Asia	73	20–40	4
Middle East	3		n.a.
S.E. Asia	320	155–220	4, 6
Australia savanna	80	100–120	″
Australia Temperate forest	22		n.a.
Eastern Asia	45	11–49	8
Central Asia	40		n.a.
Boreal Eurasia	166	106–209	9,10
Total	3325	2000–2900	11

[a]References: (1) *Leenhouts* [1998], (2) *Amiro et al.* [2001], (3) *Chen et al.* [2000], (4) *Hao and Liu* [1994], (5) *Potter et al.* [2001], (6) *Van der Werf et al.* [2003], (7) *Barbosa et al.* [1999], (8) *Wang et al.* [2001], (9) *Kasischke et al.* [2005], (10) *Soja et al.* [2004], (11) *Liousse et al.* [2004].

While burned area in the USA was 10 times higher at the beginning of the century than in the 1990s, carbon emission was only 3 times higher; our biogeochemical model lowered available biomass as a response to fires, decreasing the quantity of carbon available for later release. This decrease in biomass accounts for at least some of the low-severity surface fires that characterized the early decades of the century, though these feedbacks deserve further analysis.

[11] Carbon emission from biomass burning cannot be extrapolated directly from burned area, because the time between fires is a major controller on the carbon available for combustion. This makes the relationship between burned area and carbon emission non-linear. In the short term, recurrent fires can increase soil litter and woody debris that increase available fuel biomass [*Cochrane et al.*, 1999]. In the longer term, however, an increase in the number of fires tends to decrease available biomass and reduce the amount of carbon emitted during a fire. A 60% decrease in burned area (as in our −60% scenario in Figure 1 in 1900), induces only a 40% decrease in emissions. Subtle differences in fire history could, however, substantially alter emissions, especially when fire has an anthropogenic component.

[12] While our results are based on an explicit fire database and a biogeochemical model that is sensitive to fire history, our approach is subject to several limitations.

[13] 1. We used a constant tree mortality. We know, however, that fire management practices changed through the century. Specifically, fires in temperate and boreal forests were mostly ground fires at the beginning of the century, but crown fires have become more common recently [*Mouillot and Field*, 2005]. In some parts of the tropics, fire activity shifted from the trees to the ground as the vegetation type changed from forest to grassland. This is partly taken into account with fire feed-backs on available biomass but should be better estimated.

[14] 2. We spun-up the model based on the 1900–1910 average fire regime. Because the relationship between burned area and fire emissions depends on effects of recent fire history on fuel availability, fire emissions calculated for the early years of the 20th century are likely to be influenced by this fire regime. Similarly, we also suggest using a long fire-history reconstruction as a spin-up fire regime for present estimates of emissions from fire, instead of the 1990's average fire regime commonly used.

4. Conclusion

[15] The carbon emissions calculated here for the 1990's are similar to those from recent studies based on global remote sensing of burned area. Since our approach dynamically simulates the amount of fuel available for burning based on previous fire history, we captured the non-linear relationship between burned area and emissions. This study provides a first spatially-explicit estimate of the historical fire emissions through the 20th century that accounts for this relationship. Estimated carbon emissions based on this approach were 52–82% of current emissions in 1900, in contrast to the 10% of present sometimes assumed for the pre-industrial. The spatial distribution of emissions changed dramatically through the century, with increased emissions from the tropics and decreased emissions from the temperate and boreal zones. This is, however, a first estimate. It could be improved with better treatment of ground versus crown fires and careful validation of post fire biomass build-up.

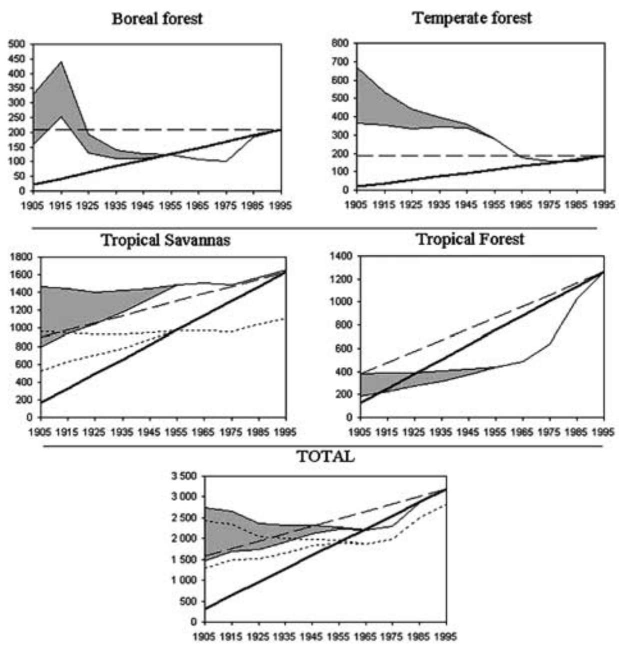

Figure 1. Temporal trend of carbon emission from biomass burning (Tg C y^{-1}) for the major terrestrial biomes. The upper line is the scenario based on the fire history of *Mouillot and Field* [2005], and the grey area represents the likely range based on −60% uncertainty in fire inputs. The dotted line represents the simulation with a lower biomass in savannas. We also represented the 10% scenario [*Crutzen and Zimmermann*, 1991] with the thick dark line, and the EDGAR-HYDE scenario [*Van Aardenne et al.*, 2001] with the dashed line.

[16] **Acknowledgments.** This research was supported by a grant from the NASA EOS IDS program to the Carnegie Institution of Washington and by the Office of Science, Biological and Environmental Research Program (BER), U.S. Department of Energy, through the Western Regional Center of the National Institute for Global Environmental Change (NIGEC) under Cooperative Agreement Nos. DE-FC03-90ER61010 and DE-FC02-03ER63613. Financial support does not constitute an endorsement by DOE of the views expressed in this article/report.

References

Amiro, B. D., J. B. Todd, B. M. Wotton, K. A. Logan, M. D. Flannigan, B. J. Stocks, J. A. Mason, D. L. Martell, and K. G. Hirsch (2001), Direct carbon emissions from Canadian forest fires 1959–1999, *Can. J. For. Res.*, *31*, 512–525.

Barbosa, P. M., D. Stroppiana, and J. M. Gregoire (1999), An assessment of vegetation fire in Africa (1981–1991): Burned areas, burned biomass, and atmospheric emissions, *Global Biogeochem. Cycles*, *13*, 933–950.

Boschetti, L., H. D. Eva, P. A. Brivio, and J. M. Grégoire (2004), Lessons to be learned from the comparison of three satellite-derived biomass burning products, *Geophys. Res. Lett.*, *31*, L21501, doi:10.1029/2004GL021229.

Chen, J., W. Chen, J. Liu, and J. Cihlar (2000), Annual carbon balance of Canada's forests during 1895–1996, *Global Biogeochem. Cycles*, *14*, 839–849.

Cochrane, M. A., A. Alencar, M. D. Schulze, C. M. Souza, D. C. Nepstad, P. Lefebvre, and E. A. Davidson (1999), Positive feedbacks in the fire dynamic of closed canopy tropical forests, *Science*, *284*, 1832–1835.

Crutzen, P. J., and P. H. Zimmermann (1991), The changing photochemistry of the troposphere, *Tellus, Ser. AB*, *43*, 136–151.

DeFries, R. S., and J. R. G. Townshend (1994), NDVI-derived land cover classification at global scales, *Int. J. Remote Sens.*, *15*, 3567–3586.

French, N. H. F., E. S. Kasischke, and D. G. Williams (2002), Variability in the emission of carbon-based trace gases from wildfire in the Alaskan boreal forest, , *107*, 8151, doi:10.1029/2001JD000480. (printed *108*(D1), 2003)

Goodale, C. L., et al. (2002), Forest carbon sinks in the Northern Hemisphere, *Ecol. Appl.*, *12*, 891–899.

Guild, L. S., J. B. Kauffman, W. B. Cohen, C. A. Hlavka, and D. E. Ward (2004), Modeling biomass burning emissions for Amazon forest and pastures in Rondonia, Brazil, *Ecol. Appl.*, *14*, S232–S246.

Hao, W. M., and M.-H. Liu (1994), Spatial and temporal distribution of tropical biomass burning, *Global Biogeochem. Cycles*, *8*, 495–503.

Houghton, R. A., K. T. Lawrence, J. L. Hackler, and S. Brown (2001), The spatial distribution of forest biomass in the Brazilian Amazon: A comparison of estimates, *Global Change Biol.*, *7*, 731–746.

Ito, A., and J. E. Penner (2005), Historical emissions of carbonaceous aerosols from biomass and fossil fuel burning for the period 1870–2000, *Global Biogeochem. Cycles*, *19*, GB2028, doi:10.1029/2004GB002374.

Kasischke, E. S., and J. E. Penner (2004), Improving global estimates of atmospheric emissions from biomass burning, *J. Geophys. Res.*, *109*, D14S01, doi:10.1029/2004JD004972.

Kasischke, E. S., E. J. Hyer, P. C. Novelli, L. P. Bruhwiler, N. H. F. French, A. I. Sukhinin, J. H. Hewson, and B. J. Stocks (2005), Influences of boreal fire emissions on Northern Hemisphere atmospheric carbon and carbon monoxide, *Global Biogeochem. Cycles*, *19*, GB1012, doi:10.1029/2004GB002300.

Krinner, G., N. Viovy, N. de Noblet-Ducoudre, J. Ogee, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I. C. Prentice (2005), A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, *Global Biogeochem. Cycles*, *19*, GB1015, doi:10.1029/2003GB002199.

Leenhouts, B. (1998), Assessment of biomass burning in the conterminous United States, *Conserv. Ecol.*, *2*, 1–25.

Liousse, C., et al. (2004), Deriving global quantitative estimates for spatial and temporal distributions of biomass burning emissions, in *Emissions of Atmospheric Trace Compounds*, edited by C. Granier, P. Artaxo, and C. E. Reeves, pp. 71–114, Springer, New York.

Mouillot, F., and C. B. Field (2005), Fire history and the global carbon budget: A 1° × 1° fire history reconstruction for the 20th century, *Global Change Biol.*, *11*, 398–420.

Potter, C. S., J. T. Randerson, C. B. Field, P. A. Matson, P. M. Vitousek, H. A. Mooney, and S. A. Klooster (1993), Terrestrial ecosystem production: A process model based on global satellite and surface data, *Global Biogeochem. Cycles*, *7*, 811–841.

Potter, C., V. Brooks Genovese, S. Klooster, M. Bobo, and A. Torregrosa (2001), Biomass burning losses of carbon estimated from ecosystem modeling and satellite data analysis for the Brazilian Amazon region, *Atmos. Environ.*, *35*, 1773–1781.

Soja, A. J., W. R. Cofer, H. H. Shugart, A. I. Sukhinin, P. W. Stackhouse, D. J. McRae, and S. G. Conard (2004), Estimating fire emissions and disparities in boreal Siberia (1998–2002), *J. Geophys. Res.*, *109*, D14S06, doi:10.1029/2004JD004570.

Still, C. J., J. T. Randerson, and I. Y. Fung (2004), Large-scale plant light-use efficiency inferred from the seasonal cycle of atmospheric CO_2, *Global Change Biol.*, *10*, 1240–1252.

Sukhinin, A. I., et al. (2004), AVHRR-based mapping of fires in Russia: New products for fire management and carbon cycle studies, *Remote Sens. Environ.*, *93*, 546–564.

Tansey, K., et al. (2004), Vegetation burning in the year 2000: Global burned area estimates from SPOT VEGETATION data, *J. Geophys. Res.*, *109*, D14S03, doi:10.1029/2003JD003598.

Van Aardenne, J. A., F. J. Dentener, J. G. J. Olivier, C. G. M. K. Goldewijk, and J. Lelieveld (2001), A 1° × 1° resolution data set of historical anthropogenic trace gas emissions for the period 1890–1990, *Global Biogeochem. Cycles*, *15*, 909–928.

Van der Werf, G. R., J. T. Randerson, J. Collatz, and L. Giglio (2003), Carbon emissions from fires in tropical and subtropical ecosystems, *Global Change Biol.*, *9*, 547–562.

Wang, C., S. T. Gower, Y. Wang, H. Zhao, P. Yan, and B. P. Bond-Lamberty (2001), The influence of fire on carbon distribution and net primary production of boreal *Larix gmelinii* forests in north-eastern China, *Global Change Biol.*, *7*, 719–730.

Y. Balkanski, Laboratoire des Sciences du Climat et de l'Environnement, F-91191 Gif-sur-Yvette, France.

C. B. Field and A. Narasimha, Department of Global Ecology, Carnegie Institution of Washington, 260 Panama Street, Stanford, CA 94305, USA.

J.-F. Lamarque, Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, CO 80305, USA.

F. Mouillot, IRD UR060/DREAM, CEFE-CNRS, 1919 route de Mende, F-34293 Montpellier Cedex 5, France. (mouillot@cefe.cnrs.fr)