FIRES IN THE BRAZILIAN AMAZON: GREENHOUSE GAS EMISSIONS FROM BURNING OF DIFFERENT ECOSYSTEMS IN RORAIMA DURING THE 1997-98 EL NIÑO EVENT

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Updated and corrected translation of:

Barbosa, R.I. and P.M. Fearnside. 1999. Incêndios na Amazônia brasileira: Estimativa da emissão de gases do efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El Niño" (1997/98). Acta Amazonica 29(4): 513-534.

4 April 2000

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Abstract

Area burned, total biomass above and below-ground, charcoal formation, burning efficiency and the carbon concentration were estimated in the different natural landscapes and agricultural systems that were exposed to fire during the El Niño event of 1997-98 in the state of Roraima, in the northernmost part of the Brazilian Amazon. Total area burned was 38,144-40,678 km^2, of which 11,394-13,928 km^2 was intact primary forest, 22,583 km^2 was savanna, 1,388 km^2 was white-sand scrub formations, and 2,780 km^2 was pasture, secondary forest and agricultural plots. Total carbon affected by the fire was 45.63×10^6 metric tons (t), with 18.90×10^6 t being released from combustion, 26.21×10^6 t from decomposition, and 0.52×10^6 t converted to charcoal (long-term carbon storage). Based on a range of published emission factors for different greenhouse gases, gross emissions from combustion were 60.8×10^6 t CO_2, 0.18-0.22 $\times 10^6$ t CH_4, 4.42-5.56 $\times 10^6$ t CO, 0.001-0.003 $\times 10^6$ t N_2O, 0.06-0.09 $\times 10^6$ t NO_x and 0.68×10^6 t NMHC (non-methane hydrocarbons). The total emission from combustion in CO_2-equivalent carbon, based on the IPCC global warming potentials of each gas over a 100-yr horizon, was 17.7-18.0 $\times 10^6$ t C.

Keywords: forest fires, carbon, Amazonia, Roraima, greenhouse effect, El Niño, global warming.

Introduction

Forest fires of great proportions in areas with high humidity in Amazonia could be considered as rare events, and only a short while ago few people would have believed that real a danger existed of such fires taking place (Uhl et al., 1988; Kauffman, 1991; Nelson and Irmão, 1998). However, in late 1997 and early 1998, fires penetrated primary forests and other types of ecosystems of the state of Roraima, located in the extreme north of the Brazilian Amazon (Barbosa, 1998a,b,c; Brazil, IBAMA, 1998; Brazil, INPE, 1998, 1999a; Shulze, 1998). Fires in savannas and transformed forest systems (secondary forests, pastures and clearings), which are traditionally burned at this time of year, spread over thousands of square kilometers of intact primary forest, provoking the death of trees and the emission of million of tons of greenhouse gases to the atmosphere. The enormous size of the fire was credited, mainly, to the drought provoked by the strong El Niño phenomenon of 1997-98. However, the occurrence of the Great Roraima Fire should not be seen as an event caused exclusively by this climatic effect. Instead, it was the result of a series of factors acting simultaneously, with the El Niño aggravating the effect of the pre-existing conditions. At present, the probability of events such as this can be expected to increase over time due to pressure of human settlements in forest areas throughout Amazonia, amplified by the increasing logging, clearing for agriculture and burning for conversion of primary forests to pastures, all increasing the vulnerability of the adjacent forests (Cochrane et al., 1999; Kauffman et al., 1988; Negreiros et al., 1996; Nepstad et al., 1999a,b).

Studies are rare that try to evaluate the risks of fires in Amazonia and their release of greenhouse gases. With the growth of human activities in the Amazon, there is a need to increase the volume of information on the impacts that this type of event can cause at regional and global levels. With this in mind, we calculated the emissions of greenhouse gases provoked by the fires in Roraima in different types of natural systems and agroecosystems that were affected by fire in 1997 and 1998. In order to calculate these emissions we estimated the following parameters: (a) the area of each natural system and agroecosystem affected, (b) the total plant biomass (above and below ground) per unit of area, (c) mortality of trees due to the fire, (d) the formation of charcoal in the systems affected, (e) burning efficiency for the different biomass categories that it comprise each system and (f) the concentration of carbon in each of these categories.

General description of the Area

Roraima is one of the former federal territories transformed into states by Brazil’s 1988 constitution, located in the northernmost portion of the Brazilian Amazon. The local population tripled between 1980 and 1998, growing from 82,018 to 260,705 inhabitants (Brazil, IBGE, 1999). The migratory explosion of this period was motivated by local public authorities in three phases: (a) at the end of the 1970s, with support of the Federal Government as part of the POLORORAIMA sub-program of the Amazonian Development Poles Program (POLOAMAZÔNIA), (b) through the “mining boom” in the Yanomami indigenous lands at the end of the 1980s, when the territory was transformed into a state and (c) in the early 1990s through state government programs to recruit migrants in other parts of the country with land-tenure problems (Barbosa, 1993). The population growth provoked an increase by 55.6 fold in the total area of deforestation, expanding from 100 km^2 in 1978 to 5,560 km^2 in 1997 (Brazil, INPE, 1999b).

The natural vegetation of Roraima is a mosaic of landscapes that range from savannas (northeast) to forests (south and west), and different types of oligotrophic (nutrient-poor) systems such as campos (grasslands), campinas and campinaranas (low woodlands on white-sand soils) in the center-south portion of the state (Silva, 1997). The annual precipitation is variable and forms a gradient from 1000 mm (in the savannas at the northeast end of the state) up to 2300 mm (southern and far western parts of the state) (Barbosa, 1997). The place with largest volume of climatic data is the capital at Boa Vista. The annual average precipitation is 1614 mm (1910 to 1995). Between September 1997 and March 1998 the precipitation was only 30.6 mm in this area, when the expected amount based on the historical average for same period would be 352 mm (Brazil, DEFARA and INMET, 1999). The relative humidity of the air was below 60% between February and March 1998 (Brazil, MAA/INMET, 1998).

Area of the Natural Systems and Agroecosystems Affected

Original area

To determine the total area affected by the fire, we estimated the original area of the original vegetation types in Roraima. We used as a base a digitization of the vegetation map of Amazonia at a scale of 1:2,500,000 (Brazil, SUDAM and IBGE, 1989), because this base uses the standard classification typology for Brazilian vegetation described by IBGE (1992). After the macrospatial determination of the types that make up the regional landscape, the map was scanned and color-coded to facilitate measurement of the original areas. Based on field observations and on a mosaic of LANDSAT-TM satellite images (1:1,000,000) (Roraima, SENAGRO and ITERAIMA, 1996), we made adjustments and modifications to the digitized map due to some inaccuracies, such as grasslands erroneously denominated as savannas or dense forests defined as ecotones. Using IDRISI (Eastman, 1995), a computer program that analyzes geographical data for spatial classification, we estimated the number of picture elements (pixels) in each vegetation type and calculated the proportional area of each category, considering the total area of Roraima as 225,116 km^2.

To estimate the net area present in 1997-98 for each original vegetation type, two types of adjustments were applied to the calculated areas: (a) for human-altered areas (rural and urban) and (b) for watercourses (major rivers). The rural areas were quantified based on the results obtained by the National Institute for Space Research (Brazil, INPE, 1999b) for areas deforested up to 1997, updated to 1998 based on the mean annual area of deforestation for the 1992-1997 period. The distribution of deforested areas among pasture, agriculture and secondary forests up to 1997-98, was obtained from the proportions based on the mean of four results: (a) the 1985 agricultural census (Brazil, IBGE, 1985), (b) the 1995-1996 agricultural census (Brazil, IBGE, 1996), (c)

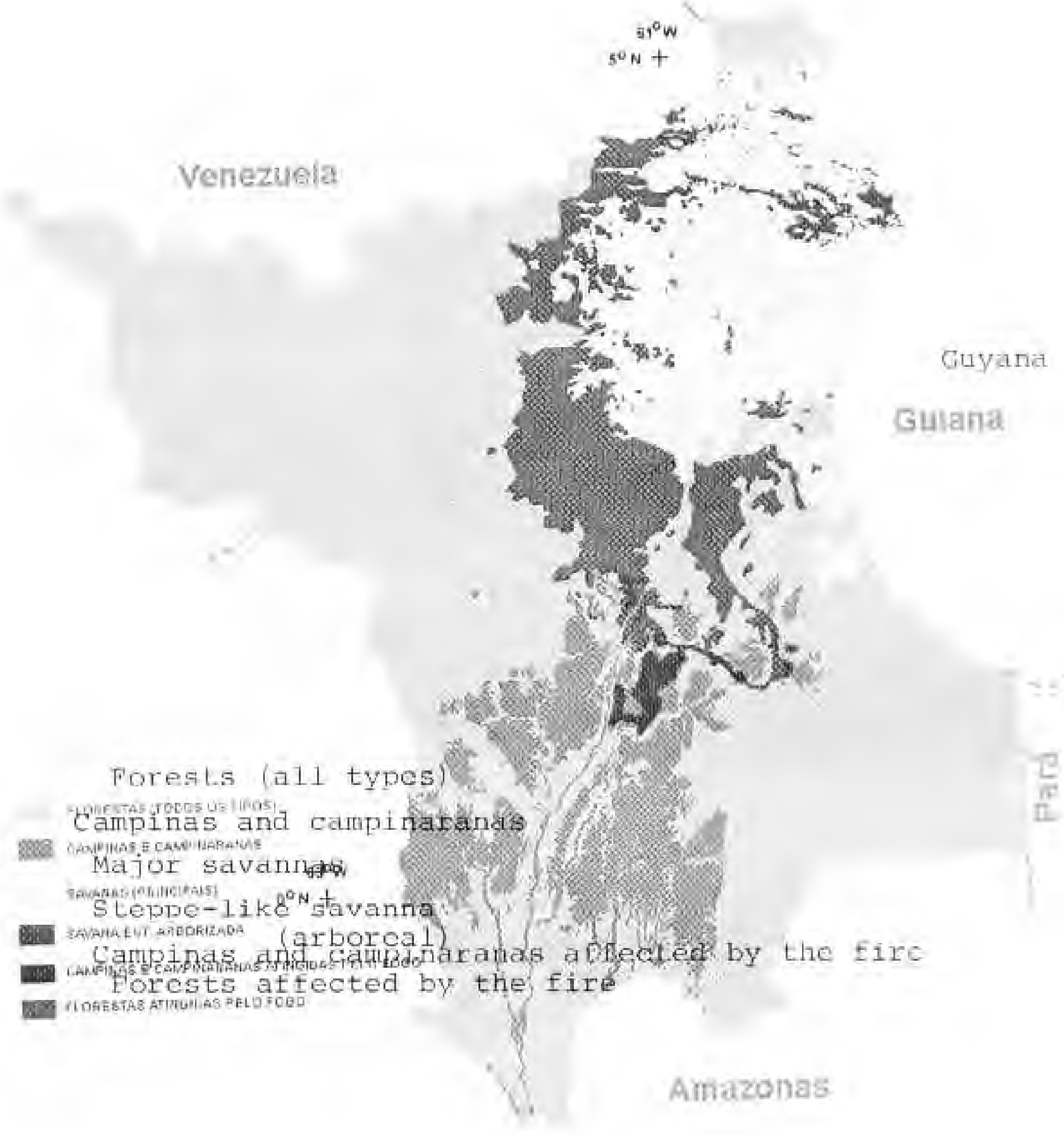
Fearnside (1996) for three equilibrium landscapes in the year 1990 and (d) the summary of the National Institute for Colonization and Agrarian Reform (INCRA) diagnostic evaluation of settlements in Roraima 1998-1999 (Luz, 1999). The areas determined for the three human-altered categories were subtracted from the forest eco-region to which each belonged, in proportion to the number of linear kilometers of existing access roads in each system, assuming a direct relationship between roads and deforested areas. The urban areas were computed by extrapolation of the mean number of pixels contained in each county seat. Adjustments were made in the same way as those for rural human-altered areas, subtracting from the area of the landscape type where the each city is located. To estimate the area of the major watercourses we used the same procedure as that used for the calculation of the typological units.

Area Burned

In order to calculate the area affected by fire in each type of forest or oligotrophic vegetation we digitized the geographical coordinates obtained in 16.5 hours of overflights by Barbosa (1998b) in the Geographical Information System (SGI/INPE, version 7.0) at the Executive Secretariat of the Ecological-Economic Zoning of Roraima (ZEE/RR). Additions and corrections were applied to the original limits of these geographical points based on field observations and, in the case of analysis of LANDSAT-TM and DMSP satellite images, based on partial reports presented by INPE (1998, 1999a). Once this was done, three blocks were established distributed along the border between the forest and the savanna. These blocks represented the major regional divisions where the fire was present: (a) Block 1: eastern section, between the left bank of the Rio Branco and the Rio Tacutu (Cantá--RR 170 Highway-–Anauá River), (b) Block 2: western section; between the right bank of the Rio Branco and the Rio Uraricoera (Caracaraí–-Rio Uraricoera) and (c) Block 3: northern section; between the left bank of the Rio Uraricoera and the right bank of the Rio Tacutu (Maracá Island--Pacaraima). In addition, the blocks were subdivided into zones for different intensities of burning in the forest: (a) high intensity, or more than 50% of the forested area affected, (b) medium intensity, or between 5 and 50% affected and (c) low intensity, or below 5% affected (but with some alterations). The intensity zones received different treatments in the analysis.

The blocks were overlayed on the vegetation base map derived from the map of SUDAM and IBGE (1989) in order to estimate the area affected by the fire in each type of forest or oligotrophic vegetation (grasslands, campinas and campinaranas). The affected area represented the total area where the fire was present (Fig. 1). However, for the forest systems, it was necessary to adjust for human-affected areas, watercourses, and other unburned landscapes, etc., in order to avoid double-counting and/or counting habitats that did not burn. In addition, the area of forest (already adjusted) also had to be adjusted based on the intensity of burning at the site. This was due to the distinct behavior of the fire in each of the intensity zones. Because of this, we defined a burning factor for each of the areas based on aerial photographs obtained in the overflights made during and after the fires. Based on this methodology, the area of forest effectively burned (the area where the fire really provoked some kind of damage to the system) was 11,394 km^2 (Table 1).

[Figure 1 and Table 1 here]



51°W
5°N +
Venezuela
Guyana
Guiana
Forests (all types)
FLORESTAS (TODOS OS TIPOS)
Campinas and campinaranas
CAMPINAS E CAMPINARANAS
Major savannas
SAVANAS (PRINCIPAIS)
Steppe-like savanna (arboreal)
SAVANA EST. ARBORIZADA
Campinas and campinaranas affected by the fire
CAMPINAS E CAMPINARANAS ATINGIDAS PELO FOGO
Forests affected by the fire
FLORESTAS ATINGIDAS PELO FOGO
Amazonas

Table 1 - Area (km^2) of intact forest affected and effectively burned in each impact zone (Total for all blocks).

Impact zone	Gross area affected (km^2)	Deductions			Net area affected (km^2)	Mean burn factor [(1)] (%)	Area effectively burned (km^2)	Mean burn factor [(2)] (%)	Area effectively burned (km^2)
		Rivers (km^2)	Other natural environments (km^2)	Human-altered environments (km^2)					
High Impact	13,687	120	981	1,789	10,797	85.1	9,189	-	-
Medium Impact	6,022	48	416	1,145	4,413	33.7	1,487	-	-
Low Impact	1,583	12	23	320	1,229	7.3	90	-	-
Sub-total	21,292	180	1,419	3,253	16,439	52.7	10,766	80.9	13,299
High Impact (SN)[(3)]	2,049	17	0	20	2,012	31.2	628	-	628
Total	23,341	198	1,419	3,273	18,451	-	11,394		13,928

(1) calculation considering the burn factor for each block and impact zone.

(2) calculation considering the burn factor determined by IBAMA (1998) for the total area of the fire in forest systems.

(3) SN - area of ecological tension; contact savanna / seasonal forest. This was determined together with the transects in the savannas because they cut this landscape type. This calculation was done separately.

Emissions estimates are subject to a high degree of uncertainty due to the fire being restricted to surface burning that did not provoke stress in the crowns of the trees in some places and, therefore, was not detected by either the aerial photographs or the satellite images. We therefore estimated a range for the burned area for the purpose of calculating emissions. The lower bound of this range was formed by the value calculated above and the upper bound by using the burning factor observed by a ground team mounted by the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA) (Brazil, IBAMA, 1998), which found 80.9% of the forest area to have some damage by the fire (effectively burned), independent of fire intensity. Applying this percentage to the total area affected, we determined the range for area effectively burned as 11,394-13,928 km^2 or, 7.4-9.0% of the whole forested area present. We use the midpoint of this interval to calculate the emissions.

Our current estimate is higher than the first results estimated by Barbosa (1998a,b) from overflights of the affected areas (7800-9200 km^2) and by INPE (1999) from LANDSAT-TM satellite images (11,730 km^2). In the first case, several areas were not quantified due to the limited aerial coverage and, in the second, the limit was due to the quality of the images and the impossibility of detecting ground fires that did not stress the leaf cover of the trees. However, in any of the above-mentioned estimates, the values are greater than the total area deforested in Roraima up to 1997 (5560 km^2) and much higher than the estimates announced previously by the government for the Great Roraima Fire (3000 km^2) (Braga, 1998).

With respect to the procedure to determine the proportion of area burned in human-affected systems (pasture, secondary forests and agricultural fields), we made four ground transects distributed in the fire-impact zones (described above): (a) Transect 1 (medium impact): 147 km between Cantá and Vila União (RR 170), (b) Transect 2 (low impact): 76 km connecting the towns of Novo Paraíso (BR 174/210), Martins Pereira, Vila Moderna and back to Novo Paraíso, (c) Transect 3 (medium impact): 60 km between the town of Mucajaí and the boundary between Iracema and Caracaraí counties and (d) Transect 4 (high impact): 64 km from side road (vincinal) No. 1 of the Apiaú settlement area, side road No. 9, cross-cutting access road (travessão) No. 9, Ribeiro Campos and side road No. 7. In each of these transects we quantified the number of lots that were affected by humans in each category (pasture, secondary forest or agricultural fields) and condition (burned or unburned). We then estimated the mean percentage of burned area by fire-impact zone in these transformed forest habitats. Of the 5776 km^2 of human-affected areas present in Roraima up to 1998 (including 220 km^2 of new clearings), we calculated that 48.1% (2780 km^2) had been effectively burned. The highest burning factors were found for the areas located in the high fire-intensity zones, for secondary forests (73.7%) and pasture (62.7%). The lowest factor was found for agricultural fields in the areas with low burning intensity (15.4%).

For the oligotrophic systems, the total burned area was estimated to be 1388 km^2, taking into consideration the procedures adopted previously. For the calculation of the total area burned in the savannas, the procedure (Barbosa, 1998b) uses the measurements made between July 1997 and June 1998 on the transects established along 540.1 km of highways that cut through all of the main types of savannas in Roraima. The burned area of this landscape totaled 22,583 km^2. A summary of the original areas and of the effectively burned area by vegetation type is given in Table 2.

[Table 2 here]

Table 2 - Original area and area effectively burned of the vegetation types (natural and agroecosystems) present in Roraima in 1997-98.

Category	Code	Group	Sub-group	Class	Area 1997-98 (km^2) Present	Effectively Burned	Percent of area burned relative to the area present
Dense forest							
	Da-0	ombrophilous forest	dense forest	alluvial	2,573	0	0.0
	Db-0	ombrophilous forest	dense forest	lowland	7,959	0	0.0
	Dm-0	ombrophilous forest	dense forest	montane	21,457	0	0.0
	Ds-0	ombrophilous forest	dense forest	submontane	72,,821	2,657	3.6
	Sub-total, Dense Forest				104,810	2,657	2.5
Non-dense forest							
	As-0	ombrophilous forest	open forest	submontane	8,197	4	0.0
	Fs-0	seasonal forest	semidecíduous	submontane	1,286	485	37.7
	ON-0	areas of ecological tension and contact		ombrophilous forest / seasonal forest	17,230	7,010	40.7
	SN-0	areas of ecological tension and contact		savanna / seasonal forest	1,975	628	31.8
	SO-0	areas of ecological tension and contact		savanna / ombrophilous forest	4,456	215	4.8
	LO-0	areas of ecological tension and contact		vegetation woody oligotrophic formations of swamps and white sand areas / ombrophilous forest	16,674	394	2.4

	Sub-total, Non-dense Forest				49,817	8,737	17.5
Non-forest	Ld-0	oligotrophic woody vegetation of swamps and white sand areas		arboreal dense	12,256	524	4.3
	La-0	vegetation woody oligotrophic of swamps and white sand areas		arboreal open	134	0	0.0
	Lg-0	vegetation woody oligotrophic of swamps and white sand areas		grassy-woody	11,573	864	7.5
	Sub-total, Oligotrophic formations				23,962	1,388	5.8
	rm-0	ecological refuge	high altitude	montane	205	32	15.5
	Sg-0	savanna	savanna	grassy-woody	15,004	7,932	52.9
	Sp-0 (2)	savanna	savanna	park	12,443	7,329	58.9
	Td-3 (2)	steppe-like savanna	Roraima grasslands	arboreal dense	2,313	1,779	76.9
	Tp-3	steppe-like savanna	Roraima grasslands	park	8,733	5,511	63.1
	Sub-total, Savannas				38,697	22,583	58.4
Human-altered(1)	Rural	pastures			3,063	1,538	50.2
		secondary forests			1,699	854	50.3
		agricultural fields			794	169	21.2
		deforestation in 1998			220	220	100.0
	Sub-total Human-altered				5,776	2,780	48.1
	Urban	cities			251	0	-
Watercourses(3)					1,803	0	-

Total area (km^2)	225,116	38,144	16.9

(1) Rural: considered as change in land use only in forest areas, especially in the vegetation types Ds, ON, Fs, LO and As; Urban: municipal seats (distributed as follows: 5 for Ds; 4 for ON; 1 for LO; 1 for SN; 2 for Sg; 1 for Sp and 1 for Tp). Areas deforested in the year of the fire were considered to be totally accessible to the fire.

(2) Sp represents, for calculation purposes, the sum of Sp and Sa, and Td represents, for calculation purposes, the sum of Td and Ta.

(3) Represents the principal rivers of Roraima

Total Original Plant Biomass

Present biomass

The calculation procedure for most of the forest eco-regions (dense and non-dense), was based on the volume-expansion method (m^3/ha) and biomass (t/ha) calculation of Brown and Lugo (1992), adjusted by the method of Fearnside (1992). For Roraima, this method underwent adjustments in the categories "dead above-ground biomass" and "below-ground biomass." For these two items, new studies were added to those adopted previously by Fearnside (1992), such as one for Maracá Island (Scott et al., 1992; Thompson et al., 1992; Nascimento, 1994; Villela, 1995) and, discarded others that did not fit the characteristics of vegetation types present in Roraima. Regional-scale volumetric data (m^3/ha) were obtained from volumes 8, 9, 10, 11, 14 and 18 of Projeto RADAMBRASIL (1975-1978), which cover the whole State of Roraima and neighboring areas where vegetation types similar. The mean total biomass (weighted by area) of all dense forests was 320 t/ha and, of non-dense forests was 279 t/ha (Table 3). In both cases, there is a reduction of 25% and 34%, respectively, with respect to the estimates by Fearnside (1997b) for carbon emissions from deforestation in Roraima in 1990.

[Table 3 here]

Table 3 - Total biomass estimated by vegetation type (t/ha) in Roraima in1997-98.

Category	Code	Biomass (t/ha)[2]			
		Above-ground		Below-ground	Total
		Live	Dead	Live	
Dense forest					
	Da-0	275	21	47	343
	Db-0	276	21	47	345
	Dm-0	232	18	40	290
	Ds-0	261	20	45	326
	Weighted average, Dense forest	257	20	44	320
Non-dense forest					
	Os-0	226	17	39	283
	Fs-0	226	17	39	283
	ON-0	226	17	39	283
	SN-0	158	12	27	197
	SO-0	158	12	27	197
	LO-0	234	32	40	306

	Weighted average, Non-dense forest	220	22	38	279
Non-forest					
	Ld-0	39.8	7.8	69.0	117
	La-0	33.8	5.0	21.3	60
	Lg-0	5.8	3.7	42.0	52
	Weighted average, Oligotrophic formations	23.3	5.8	55.7	85
	rm-0	2.7	0.4	10.0	13
	Sg-0	2.9	0.4	10.9	14
	Sp-0	5.4	0.6	20.3	26
	Td-3	26.1	2.9	66.5	95
	Tp-3	5.2	0.4	13.3	19
	Weighted average, Savannas	5.6	0.6	17.8	24
Human-altered	Rural:				
	pasture [(1)]	11.2	65.5	12.2	89
	secondary forest	30.9	112.4	22.8	166
	agricultural fields	0.4	59.3	9.5	69
	deforestation, 1998	0.0	271.2	43.2	314
	Weighted average, Human altered	15.1	86.3	16.1	117
	Urban:	-	-	-	-

Watercourses[3]	-	-	-	-
Total area (km²)				

(1) Average of two pastures in the area of Apiaú, Roraima. Live above-ground is the sum of grass and small herbs and bushes. Dead above-ground encompasses all plant material above the ground that is part of the mass of the pasture and the mass of the former forest (logs, for instance). (Barbosa & Fearnside, 1996).

(2) Methodology for obtaining the biomass (live and dead) above- and below-ground:

Da – Volume-expansion method of Brown & Lugo (1992), corrected with the adjustment factors of Fearnside (1992), modified for above-ground dead mass and below-ground live mass.

Db -- Volume-expansion method of Brown & Lugo (1992), corrected with adjustment factors of Fearnside (1992), modified for above-ground dead mass and below-ground live mass.

Dm -– Volume-expansion method of Brown & Lugo (1992) corrected with the adjustment factors of Fearnside (1992), modified for above-ground dead mass and below-ground live mass. (two values were considered : a) Roraima sedimentary plateau (10.7%) and b) Parima mountains (89.3%)).

Ds -– Volume-expansion method of Brown & Lugo (1992) corrected with the adjustment factors of Fearnside (1992), modified for above-ground dead mass (two values were used (simple average): a) low chain of mountains of the Guianan complex and b) dissected landscape of the Guianan complex).

As - For lack of local references, the value determined for ON was used.

Fs - For lack of local references, the value determined for ON was used

ON - Volume-expansion method of Brown & Lugo (1992) corrected with the adjustment factors of Fearnside (1992), modified for above-ground dead mass and below-ground live mass.

SN - Volume-expansion method of Brown & Lugo (1992) corrected with the adjustment factors of Fearnside (1992), modified for above-ground dead mass and below-ground live mass.

SO - For lack of references, the value for SN was used (this was modified starting from the values obtained for "La" (RADAM), and compared to the results of Silva (1993))

LO - Used as the average of three values to compose the live and dead above-ground biomass: a) volume expansion; b) "bana alta" (tall Amazon caatinga), by Bongers et al. (1985) and c) Amazon Savanna, in Venezuela, by Klinge & Herrera (1983). For below-ground biomass, the average of all the remaining of the groups was used, to derive the percentage relative to the above-ground live biomass.

Ld - For lack of local references, the value for Venezuelan "low bana" (Low Amazon Caatinga), in Venezuela, of Bongers et al. (1985) was used

La - Obtained starting from the fieldwork of Cavalcanti & Higuchi (in press.) in the south of Roraima in the landscape denominated "Campina/Campinarana." The values of these authors for fresh weights were converted to dry weight following the methodology of Carvalho et al. (1995) and Higuchi et al. (1997). The correction for the mass of other components was made using the averages obtained by Bongers et al (1985) for the component "others" in Venezuelan bana.

Lg - For lack of local references, the value determined for Venezuelan "open" bana (Open Amazon caatinga) by Bongers et al. (1985) was used.

rm - Estimate based on the low stratum of the landscapes Sg, Sp and Tp.

Sg – Above-ground biomassl (live and dead) from Barbosa (1998) and, below-ground biomass, assumed as the average of the results found by Castro & Kauffman (1998), for " clean " field and campo sujo ("dirty" grassland) to a depth of 2 m, near Brasília (3.78 times the live above-ground mass).

Sp (and Sa) – Above-ground biomass (live and dead) from Barbosa (1998) and, below-ground biomass, assumed to be the obtained average of the results of Castro & Kauffman (1998), for campo limpo ("clean" grasslands) and campo sujo "dirty" grasslands to a depth of 2 m near Brasília (3.78 times the live above-ground mass).

Tp - Biomass above ground (live and dead) according to Barbosa (1998) and, below-ground biomass, assumed to be the average of the results of Castro & Kauffman (1998) for "open" cerrado (central Brazilian savanna) and "dense" cerrado to 2-m depth near Brasília (2.55 times the live above-ground mass).

Td (and Ta) - The value of Fearnside et al. (nd) - for above-ground biomass was assumed (29 t/ha) and was partitioned between live and dead fractions, based on the average of the other values for savanna found in the table. For below-ground biomass, the method was the same as that adopted for Tp.

Pasture - Live above-ground biomass is the simple average of two samplings in the area of Apiaú, Roraima (Barbosa & Fearnside, 1996) (the value for dead above-ground biomass was considered to be the same as that determined for secondary forest - both systems are derived from deforestation; because pasture is a deforested landscape, the below-ground biomass was considered as an average of the below-ground biomass of all forest systems).

Secondary forest – Above-ground biomass is assumed to be the value determined for 6-7 year-old secondary forest in the area of Apiaú, Roraima (Fearnside et al., nd) (dead biomass was considered to be original-forest remains in the same study and, below-ground biomass is calculated using the same relationship as that described above for pasture).

Agricultural fields - Assumed to be the same as that given by Fearnside (1997a) for "farmland" (the value for above-ground dead biomass was considered to be the simple average of the dead above-ground mass of pastures and secondary forests and the live biomass of newly deforested areas - all considered transformed environments.

Recently deforested - Considered as the biomass present at the time of felling. This was derived from the values determined for Ds, ON, Fs, LO and As. The dead above-ground biomass is that calculated for this group plus the pre-existing litter (fine and coarse).

For the non-forest oligotrophic systems (grasslands, campinas and campinaranas), besides the RADAMBRASIL timber volume data, we used existing studies in similar eco-regions in Venezuela (Bongers et al., 1985; Klinge and Herrera, 1983) and a study carried out in the south of Roraima by a team from the Tropical Forestry Department at INPA in 1992 (Niro Higuchi, personal communication). The values for total biomass varied from 52 t/ha to 117 t/ha for these systems. The values for other non-forest eco-regions (savannas), were adjusted based on studies of R.I.B. that are underway since 1994 for estimation of emissions of greenhouse gases from burning in Amazonian savannas. To estimate below-ground biomass in savannas we used the proportions obtained by Castro and Kauffman (1998) in the cerrado savannas of central Brazil. In general, the total biomass (above- and below-ground) of these systems was 13-95 t/ha, depending on the proportion of trees present in each habitat.

Estimate of the pre-existing biomass in the human-affected systems were derived as follows: (a) pastures we used the simple average among two pastures (7 and 9 years of age) studied in the area of Apiaú, Roraima, by Barbosa and Fearnside (1996); for above-ground biomass we considered the sum of the mass of grass and small non-woody herbs. For the above-ground biomass killed we considered the same study and determined the average of the whole mass of the forest residues found in the two pastures; for the below-ground biomass we considered the existing mean proportions in the other transformed systems to determine the percentage with respect to live above-ground biomass; (b) secondary forests: we used the results obtained by Fearnside et al. (nd) in a five-year-old secondary forest in the area of Apiaú, Roraima; (c) agricultural fields: we assumed the value determined by Fearnside (1997a) for live above-ground biomass and we used the same proportional result (live/dead) for dead above-ground biomass in the pastures at Apiaú; (d) 1998 deforestation: we considered as the present biomass at the time of cutting (before the burn); this value was estimated by weighing, based on area of each of the other forest types that are subjected to deforestation in Roraima. The results for total biomass in these systems were: 89 t/ha (pasture), 166 t/ha (secondary forest), 69 t/ha (agricultural fields) and 314 t/ha (recently deforested areas).

Forest arboreal biomass killed by the Fire

To survey the biomass killed in the different forest types we carried out post-fire studies in three areas affected by the fires: (a) Apiaú/Ribeiro Campos, (b) Trairão/Tepequém and (c) Paredão, all in the ON type (area of ecological tension or ecotone and contact between ombrophilous and seasonal forests). For the arboreal species above 10 cm diameter at breast height (DBH), we established seven 750-m^2 transects, three of which were at the first site, three at the second and one at the third. Each transect was divided into 6 quadrats of 125 m^2 (5 m × 25 m), separated by a distance of 20 m. In each quadrat we measured the DBH of all individuals killed (dry cambium and/or crown with dry leaves) and we applied the general formula for biomass determination (fresh weight) for tropical forest trees given by Carvalho et al. (1995) and Higuchi et al. (1997, 1998). The value was adjusted for dry weight (t/ha) following the recommendations of these authors. With this, we reached the result of 5.8 t/ha for the 2173 individuals killed with DBH below 10 cm and 17.4 t/ha for the 46 individuals killed with DBH above 10 cm (Table 4).

[Table 4 here]

Table 4 - Mortality of individuals (number/ha) and of above-ground arboreal biomass (t/ha) determined in three studies after the burn in Roraima.

Parameters	Simplified diameter classes (cm)						Above-ground arboreal average		Source
	< 5		5-10		> 10		Individuals	Biomass	
	no./ha	t/ha	no./ha	t/ha	no./ha	t/ha	no./ha	t/ha	
Total individuals or biomass[(1)]	2,120	5.6	307	19.9	585	219.7	3,011	245.2	
Dead	1,933	3.0	240	2.8	46	17.4	2,219	23.3	This study
(%) mortality	91.2	54.2	78.3	14.1	7.9	7.9	73.7	9.5	
Total individuals or biomass[(2)]			340		425				
Dead			122	3.0	68	16.1			Santos et al. (1998)
(%) mortality			35.9		16.0				
Total individuals or biomass					616				

Dead	50	Brazil, IBAMA (1998)
(%) mortality	8.1	

(1) For DBH ∃ 10 cm in the following locations: Apiaú/Ribeiro Campos, Trairão/Tepequém and Paredão; for DBH < 10 cm in the following locations: Apiaú/Ribeiro Campos.
(2) Area of Apiaú/Mucaja.í
(3) Includes palm trees. Evaluation of the areas of the arc of fire connecting the areas of Roxinho, Caracaraí, Apiaú, Pacaraima and Trairão.

These values are similar to the 16.1 t/ha determined by Santos et al. (1998) for individuals killed above 10 cm DBH in the Apiaú area and they are similar to the results of the survey of individual mortality that the IBAMA teams carried out in five areas affected by the fires, which found a mean of 50 dead individuals/ha with DBH above 10 cm, including palms (Brazil, IBAMA, 1998). However, the variation in the values distributed among the diameter classes and sites reflects a great variation among the areas studied, in spite of all of the areas being classified as belonging to the same forest category (ON). With respect to other studies carried out in similar situations, our percentage value for individual mortality (7.9% for DBH above 10 cm) is 5.5 times less than to the 44% found for burned areas derived from forests that has been selectively logged in Paragominas (Holdsworth and Uhl, 1997) and, 7.6 times less than the 60.3% mean mortality found eight months after the burn at four other sites in Paragominas county in already disturbed forest areas (Kauffman, 1991). In terms of total above-ground arboreal biomass killed, our values represent less than half of the 50 t/ha of dead mass for a light fire (area burned only once) studied by Cochrane and Schulze (1999) south of the town of Tailândia, Pará. Although differences exist between natural forest structures and those disturbed by human action, the comparisons mentioned above suggest the need for continued post-burn monitoring in Roraima. Dramatic biomass change and an increased number of individuals killed are expected, even in little-affected systems.

Arboreal biomass killed below 10 cm DBH was estimated by counting the individuals (dead and alive) in two 375-m^2 transects (3 quadrats of 125 m^2) established at Apiaú and Ribeiro Campos. Individuals were divided into two categories: (a) smaller than 5 cm DBH (including all seedlings and saplings of different heights) and (b) 5-10 cm DBH. Biomass in these two categories was estimated based on the proportion of the individuals present (dead and alive) and the values determined for biomass of trees below 10 cm DBH in the estimates described above for total biomass by forest type.

Formation of Charcoal

To estimate the amount of charcoal formed by the fire in the primary forest systems, we established 20 1-m^2 quadrats, at the Apiaú and Ribeiro Campos sites. The quadrats were distributed as follows: (a) 11 where the fire was considered to be of high intensity, (b) 5 in habitats with damage of average intensity and (c) 4 in habitats with damage of low intensity. In each quadrat all pieces of charcoal on the ground were collected. Wet weight was measured and dry weight was determined later by drying the material to constant weight in an electric oven at 105^oC. We considered the values found by intensity of burning in order to establish a mean result for each block and for the burned area as a whole. The mean result was 229.7 kg of charcoal formed per hectare affected by the fire in the forest areas (Table 5). This value is, on average, 0.089-0.104% of the total above-ground biomass in the forests (dense and non-dense) of Roraima. This charcoal formation percentage differs substantially from the values found for burns of transformed systems such as pasture (2.5-3.8%), secondary forests (0.6 - 2.0%) and recent clearings (1.9%) (Barbosa and Fearnside, 1996; Fearnside, 1997a,b; Fearnside et al., nd).

[Table 5 here]

Table 5 - Formation of superficial charcoal (t/ha) due to the fires in forest systems of Roraima (1997-98) by fire intensity zone and block.

Forest burn intensity category	Simple average by Intensity (kg/ha)	Area effectively burned in each Block[2]			
		Block 1 (km^2)	Block 2 (km^2)	Block 3 (km^2)	Total
HIGH [1]	258.7	1,208	5,278	2,702	9,817
AVERAGE	51.3	793	459	235	1,487
LOW	9.8	51	27	11	90
Weighted average by block (kg charcoal/ha)	-	172.3	241.0	241.2	229.7

(1) We weighted the average for the high-intensity zone because 6 quadrats were sampled at terra-firme (upland) locations (173.9 kg/ha in 84% of the affected area) and 5 in foothill locations (707.3 kg/ha or 16% of the affected area).

(2) The value here used was determined the method of the fire-impact zones (11,394 km^2).

Burning efficiency

For estimating burning efficiency in forest we divided the plant material into three groups: (a) fine litter: leaves and twigs less than 2 cm in diameter that had fallen on the forest floor, (b) coarse litter: logs and dead branches on the ground with diameter over 2 cm and (c) other components: other plant categories that are neither litter nor trees. The percentage estimates of burning efficiency were based on the average of the measurements made by Uhl et al. (1988) in experimental burns in San Carlos (Venezuela) and with the data collected by IBAMA at Trairão and Roxinho (Brazil, IBAMA, 1998). The largest and the smallest values were distributed among the forest burn intensity zones and, on average, they were between 4.5% for the coarse litter in the low-intensity zone and 97.6% for fine litter in the high-intensity zone (Table 6). For the savannas we used data from the studies that R.I.B. has been carrying out since 1994 in the study area. The values were lumped into a single category of burning intensity, ranging from 28% to 94.6%, depending on the biomass class. For human-altered environments burning efficiency ranged from 11.9% to 97.6%.

[Table 6 here]

Table 6 - Burning efficiency (%) by fire-intensity zone (forest) and by landscape type, due to the fires in Roraima (1997-98).

Category	Code	Fine litter			Coarse litter			Other Components		
	Da-0 Db-0 Dm-0	Low	Average	High	Low	Average	High	Low	Average	High
Forest (Dense and Non-dense) (1)	All Types	69.3	83.4	97.6	4.5	39.2	73.8	4.5	28.0	51.5
Non-dense forest	All	69.3	83.4	97.6	4.5	39.2	73.8	4.5	28.0	51.5
	As-0									
	Fs-0	69.3	83.4	97.6	4.5	39.2	73.8	4.5	28.0	51.5
	ON-0	69.3	83.4	97.6	4.5	39.2	73.8	4.5	28.0	51.5

	SN-0	69.3	83.4	97.6	4.5	39.2	73.8	4.5	28.0	51.5
	SO-0	69.3	83.4	97.6	4.5	39.2	73.8	4.5	28.0	51.5
	LO-0	69.3	83.4	97.6	4.5	39.2	73.8	4.5	28.0	51.5
Non-forest(2)	Ld-0	-	-	83.4	-	-	39.2	-	-	28.0
		-	-		-	-		-	-	
	La-0	-	-		-	-		-	-	
		-	-		-	-		-	-	
	Lg-0	-	-	85.5	-	-	22.6	-	-	59.4
		-	-		-	-		-	-	
		-	-		-	-		-	-	
	rm-0	-	-	85.5	-	-	22.6	-	-	59.4
	Sg-0	-	-	81.9	-	-	18.6	-	-	80.9
	Sp-0	-	-	84.2	-	-	22.9	-	-	63.7
	Td-3	-	-	85.5	-	-	22.6	-	-	59.4
	Tp-3	-	-	90.4	-	-	26.3	-	-	33.7
Human-altered	Pasture	-	-	45.6	-	-	11.9	-	-	82.1
	Secondary forest	-	-	91.3	-	-	31.6	-	-	80.0
	Agricultural fields	-	-	91.3	-	-	21.8	-	-	81.1
	Deforestation(3)	-	-	97.6	-	-	30.0	-	-	75.7
	Urban									

Watercourses[3]

Total area (km^2)

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(1) We considered a general average for all types of forest systems.

(2) For non-forest systems we took in consideration the values determined for the local savannas; for the oligotrophic areas values are based on the biomass present in each system.

(3) Burning efficiency for thick litter and other components in "deforestation" was considered as the same value observed in Altamira by Fearnside et al. (1999). For fine litter, we used the simple average of the results found by the same authors in Manaus and Altamira.

(4) Non-forest and human-altered systems were considered to always be in zones of high intensity because these areas could not be differentiated into other categories due to the great impact that the fire provoked in these systems.

Concentration of Carbon

The concentration of carbon (%C) in the vegetation categories of forest systems was estimated based on the measurements of Barbosa and Fearnside (1996) and Fearnside et al. (nd) in wood pieces and other forest components found in pastures and secondary forests in the Apiaú area. For the carbon concentration in the savannas, we use the results obtained by R.I.B. in his studies of greenhouse gas emissions from burning and decomposition in savannas in Roraima. The results ranged from 33.0% C for litter of grassy-woody savanna up to 64.4% C for charcoal found in the different environments (Table 7).

[Table 7 here]

Table 7 – Mean carbon concentration (% C) in the ecological systems of Roraima.

Category	Code	Dead trees (above- and below-ground)	Litter (fine + coarse)	Other components	Charcoal (long-term pool)
Forest (dense and non-dense)	All forest types	48.2	39.8	48.2	64.4
Non-forest	Ld-0 La-0	48.2	39.8	48.2	64.4
	Lg-0	46.7	36.0	38.8	64.4
	rm-0	46.7	36.0	38.8	64.4
	Sg-0	47.2	33.0	36.0	64.4
	Sp-0	46.8	36.7	40.2	64.4
	Td-3	46.7	36.0	38.8	64.4
	Tp-3	46.1	38.4	40.2	64.4
Human-altered	Pasture	44.5	47.8	43.8	64.4
	Secondary forest	44.5	42.9	45.5	63.2
	Agricultural fields	44.5	45.4	44.6	63.8
	Deforestation	44.5	45.4	44.6	63.8

Fate of Carbon Affected by the Fire

The total mass of carbon affected by the fires in Roraima in 1997-98 was 45.63 million tons of carbon (t C). This carbon followed three different pathways: (a) carbon emitted instantaneously to the atmosphere by combustion: 18.90 million t C or 41.4% of the total, (b) carbon stored in the form of charcoal on the ground in the affected systems: 0.52 million t C or 1.1% and (c) decomposition of plant material killed by the fire (mainly trees): 26.36 million t C or 57.4% (Table 8). Of the total affected carbon, 72.1% (32.9 million t C) can be attributed to primary forest systems that were exposed to fire. The systems that contributed least were the oligotrophic formations (other non-forest systems) with 2.7% of the total affected carbon (1.25 million t C).

[Table 8 here]

Table 8 - Fate of carbon affected by the burning of vegetation in Roraima (1997-98).

System	Combustion		Charcoal		Decomposition		Total	
	(10^6 t)	(%)	(10^6 t)	(%)	(10^6 t)	(%)	(10^6 t)	(%)
Forests	12.78	67.6	0.19	35.9	19.93	75.6	32.90	72.1
Savannas	2.34	12.4	0.0006	0.1	4.80	18.8	7.14	15.7
Other Non-forest systems	0.26	1.4	0.0003	0.1	0.99	3.8	1.25	2.7
Human-altered	3.52	18.6	0.33	64.0	0.48	1.8	4.34	9.5
Total	18.90	41.4	0.52	1.1	26.21	57.4	45.63	100.0

(1) Combustion = instantaneous emission at the time of passage of the fire; charcoal = charcoal formed by the incomplete combustion of plant material; decomposition = material that died and began decomposing after passage of the fire.

Gross emissions of Greenhouse Gases

To estimate the amount of greenhouse gases (CO_2, CH_4, CO, N_2O, NO_x and NMHC) emitted to the atmosphere, we adopted the method of Fearnside (1997a,b), using the global warming potentials (GWPs) of the Intergovernmental Panel on Climate Change (IPCC) for a 100-year time horizon (Schimel et al., 1996), without adjustments for uptake of carbon from the atmosphere by the terrestrial biota. This method was applied to two trace-gas emission scenarios: (a) low scenario (low trace-gas emission) and (b) high scenario (high trace-gas emission). We did not estimate the net emission of gases by the decomposition of the plant material killed in the fires, or the uptake of carbon by artificial or natural sinks. Therefore, our calculations do not reflect either the annual balance of the fire event or net committed emissions, but rather the gross emission of gases estimated starting from the carbon emitted instantly by combustion at the time the fire passed.

The total of emitted gases, in CO_2 equivalent, was 65.0-66.1 million tons, depending on the scenario for trace-gas emissions (Table 9). This corresponds to 17.7-18.0 million t of CO_2-equivalent carbon. Most of these emissions (68.1%) were attributed to the primary forest systems affected by the fire (12.1-12.3 million tons of CO_2-equivalent carbon), followed by the human-altered environments (3.3-3.4 million), savannas (2.1 million t) and other non-forest systems (0.2 million t). Even assuming a reduction of 25-34% in the previous estimates of biomass per unit of forest area, our mean total value (17.9 million t of CO_2-equivalent C), is equal to 4.1-4.2 times the value calculated by Fearnside (1997b) for deforestation emissions in Roraima, considering all net committed emissions for the year of 1990 and all sources and sinks of carbon in that year (4.3-4.4 million t CO_2-equivalent C).

[Table 9 here]

Table 9 – Gross emissions of greenhouse gases by combustion in the Great Roraima Fire of 1997-98.

Low Scenario

Gas	GWP (1)	Intact forests	Savannas	Other non-forest ecosystems	Human-altered systems	Total	Intact forests	Savannas	Other non-forest ecosystems	Human-altered systems	Total	Contribution of each gas (%)
		In 10^6 t of gas emitted					In 10^6 t of CO_2 gas equivalent					
CO_2	1	41.12	7.46	0.83	11.34	60.76	41.12	7.46	0.83	11.34	60.76	93.53
CH_4	21	0.13	0.01	0.00	0.04	0.18	2.79	0.18	0.02	0.77	3.76	5.79
CO	0	3.18	0.32	0.04	0.88	4.42	0.00	0.00	0.00	0.00	0.00	0.00
N_2O	310	0.00	0.00	0.00	0.00	0.001	0.31	0.04	0.00	0.09	0.44	0.68
NO_x	0	0.04	0.01	0.00	0.01	0.06	0.00	0.00	0.00	0.00	0.00	0.00
NMHC	0	0.61	0.02	0.00	0.05	0.68	0.00	0.00	0.00	0.00	0.00	0.00
Total of CO_2 gas equivalent							44.2	7.7	0.9	12.2	65.0	
CO_2-C equivalent							12.1	2.1	0.2	3.3	17.7	

High Scenario

Gas	GWP (1)	Intact forests	Savannas	Other non-forest ecosystems	Human-altered systems	Total	Intact forests	Savannas	Other non-forest ecosystems	Human-altered systems	Total	Contribution of each gas (%)
		In 10^6 t of gas emitted					In 10^6 t of CO_2 gas equivalent					
CO_2	1	41.12	7.46	0.83	11.34	60.76	41.12	7.46	0.83	11.34	60.76	91.88
CH_4	21	0.16	0.01	0.00	0.04	0.22	3.33	0.31	0.03	0.92	4.59	6.94
CO	0	3.98	0.43	0.05	1.10	5.56	0.00	0.00	0.00	0.00	0.00	0.00
N_2O	310	0.00	0.00	0.00	0.00	0.003	0.56	0.06	0.01	0.15	0.78	1.18
NO_x	0	0.06	0.01	0.00	0.02	0.09	0.00	0.00	0.00	0.00	0.00	0.00
NMHC	0	0.61	0.02	0.00	0.05	0.68	0.00	0.00	0.00	0.00	0.00	0.00
Total of CO_2 gas equivalent							45.0	7.8	0.9	12.4	66.1	
CO_2-C equivalent							12.3	2.1	0.2	3.4	18.0	

(1) GWP= Global warming potential (value adopted by the IPCC to weight to trace gases over a 100-year time horizon).

(2) The low and high scenarios refer to the emission factors for non-CO_2 trace gases.

(3) The emission factors that determine the amount of gas emitted per unit weight of carbon combusted for forests and deforestation were taken from Fearnside (1997a) and IPCC/OECD (1997), and for savannas and other non-forest systems from Hurst et al. (1996) and IPCC/OECD (1994).

Conclusions

Forest fires initiated by anthropogenic burning in Amazonia in years of severe drought, such as the one during the El Niño event in Roraima in 1997-98, can provoke emission of large amounts of greenhouse gases to the atmosphere. Our results indicate that the primary forests affected by the fire in 1997-98 in Roraima emitted 12.1-12.3 million tons of CO_2-equivalent carbon. Considering that every year many burns penetrate forests all over Amazonia, it is possible that the estimates of carbon released annually through forest disturbances in the Brazilian Amazon are now larger than the 0.3×10^9 t/yr that have been calculated for deforestation (Fearnside, 1997a,b; Nepstad et al., 1999b). Human pressure, the expansion of disturbed areas for clearings, pasture, agricultural fields and selective logging over the last 20 years in Roraima, the ignition source that provoked the fires were lead to burning 38,144-40,678 km^2 of different habitats, including 11,394-13,928 km^2 of primary forests. The El Niño event merely maximized the effects of the increase in human activity in the forest systems of Roraima over the few last years, indicating that the risk of fires of this magnitude occurring throughout Amazonia is greater than was thought in the past.

ACKNOWLEDGMENTS

Ademir J. dos Santos, Antônio C. Catâneo and Jaime França, of IBAMA, Carlo Zacquini of the Pro-Yanomami Commission (CCPY/RR) and the Indigenous Council of Roraima (CIR) contributed flight time from their projects to facilitate the measurements of area burned. Rogério Gribel (INPA), Jeanine Felfili (University of Brasília), Ary T. O. Filho (Federal University of Lavras), Marco Aurélio Fontes (Federal University of Lavras) and Marcelo T. Nascimento (Universidade do Norte Fluminense-UNEF) kindly made available their original field data for comparisons with our base of calculations of the mortality of individuals in the forest systems. Viriato de Souza Cruz (ZEE/Roraima), made possible the measurements of burned area by permitting us to use equipment and software at the

Executive Secretariat of ZEE/Roraima. Thelma Krug and João Roberto dos Santos, both of INPE, provided information that facilitated the final adjustment of the areas affected by the fires. Sebastião Pereira do Nascimento and Herundino Ribeiro do Nascimento (Convention between INPA and the Government of the State of Roraima) assisted in the fieldwork. This is an updated and corrected translation of Barbosa and Fearnside (1999).

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Figure Legend

Figure 1 – Gross areas of forest and oligotrophic systems (campinas and campinaranas) affected by the fires.

List of Tables