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# MODELING BIOMASS BURNING EMISSIONS FOR AMAZON FOREST AND PASTURES IN RONDÔNIA, BRAZIL

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*Abstract.* As a source of atmospheric carbon, biomass burning emissions associated with deforestation in the Amazon are globally significant. Once deforested, these lands continue to be sources of substantial burning emissions for many years due to frequent pasture burning. The objective of this research was to quantify biomass-burning emissions at a local scale. We estimated carbon emissions from three sources: fires associated with primary forest slash, regenerating forest slash, and pastures. The study was conducted on a 94 370-ha section of land surrounding Jamari, Rondônia, Brazil. In the emissions computation, we integrated site-specific, ground-based data (biomass, emission factors for flaming and smoldering combustion, and combustion factors for land-cover types) with a Landsat TM land cover change map of the study area for 1984–1992. This map was used to ascertain changes in land cover based on TM image dates during a period of early colonization and rapid deforestation in Rondônia. Emissions of CO, $CO_2$, $CH_4$, and other hydrocarbon trace gases were calculated. Between 1984 and 1992, we found $CO_2$ emissions generated by primary forest slash burning were 694 379 Mg C (920 kg $C \cdot ha^{-1} \cdot yr^{-1}$) and regenerating forest slash burning contributed 23 436 Mg C (31 kg $C \cdot ha^{-1} \cdot yr^{-1}$), whereas cumulative pasture burning produced 238 180 Mg C (316 kg $C \cdot ha^{-1} \cdot yr^{-1}$). CO and $CH_4$ followed the same trends by land cover type. Primary forest slash burns contributed 73% of the total C emissions whereas burning regenerating forest slash and pasture produced 2% and 25%, respectively. The major finding of this work is the identification of pasture burning as a potentially important source of pyrogenic emissions, but better data on biomass and combustion efficiency could confirm this finding. Further we demonstrated a novel method for estimating area burned that links land cover type and change to burn frequency.

*Key words: Amazon; biomass burning; Brazil; carbon; land-cover change; land use; pasture; primary forest; regenerating forest; Rondônia; trace gas emissions.*

## Introduction

As established since the early 1980s, it is now well known that biomass burning, particularly in the tropics, affects atmospheric chemistry globally by contributing tremendous amounts of greenhouse gases and aerosols to the troposphere (Crutzen et al. 1985, Andreae et al. 1988, Crutzen and Andreae 1990, Houghton 1990, Ward et al. 1992, Andreae 1993, Allen and Miguel 1995, Fearnside 1997, Andreae and Merlet 2001). Increased concentrations of trace gases, such as $CO_2$, $CH_4$, $N_2O$, and $O_3$, from biomass burning are potentially involved in the warming effect of Earth by preferentially absorbing thermal infrared light in the troposphere and redirecting this energy back to the Earth (Baird 1999). Although the quantity of $CH_4$ emissions from burning are ~0.5–1.5% of $CO_2$, it has 25 times the radiative effect of $CO_2$ (Houghton 1990). Important tropical sources of $CH_4$ include deforestation, cattle ranching, land-use-related burning (i.e., pastures, grassland, and fuel wood), termite activity, and rice cultivation (Houghton 1990, Leng 1993, Fearnside 1997). CO emissions generated by smoldering combustion (i.e., combustion of coarse wood) are not radiatively active, but CO interacts with the hydroxyl radical ($OH^{\bullet}$) and reduces the oxidizing capacity of $OH^{\bullet}$ to remove gases such as $CH_4$ from the troposphere (Fearnside 1997, Baird 1999). $CO_2$, CO, and $CH_4$ represent the largest mass of carbon emissions from biomass burning, however, hydrocarbon trace gases have more recently come to the attention of atmospheric chemists as to the detrimental role of these trace gases in atmospheric chemistry. Hydrocarbons make tropospheric $O_3$ when $NO_x$ is present (Marufu et al. 2000). Also, hydrocarbons utilize $OH^{\bullet}$, decreasing $OH^{\bullet}$ pools for removing detrimental tropospheric gases. Further, some hydrocarbons can be used as traces for deter-

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mining the source of burning emissions (Avery et al. 2001).

Uncertainties exist in factors involved in estimating the net release of carbon to the atmosphere in the tropics and include (1) carbon stocks of tropical forests, especially those subject to thinning and degradation, regenerating forests, and pastures; (2) deforestation rates (including logging and associated forest damage), and subsequent use (i.e., permanent or temporary clearing) of deforested areas; (3) forest loss due to undetected surface fires and accidental fires spreading from agricultural areas in standing forests; and (4) interannual seasonal differences influencing fire activity (Houghton 1991, Cochrane et al. 1999, Nepstad et al. 1999, Houghton et al. 2000). These factors vary over time and location. Houghton (1991) reported that some of the variation in deforestation rates was attributed to measurement, but primarily the variation appears to be from year-to-year deforestation influenced by the length of the dry season and, hence, length of the burning season. Further, the consequences of severe drought associated with El Niño events on vegetation have made ecosystems more vulnerable to fire and made fire seasons more severe. Estimates of burning are typically made using advanced very high resolution radiometer (AVHRR) fire products depicting locations of fires burning during NOAA satellite overpasses (Tucker et al. 1984, Setzer and Pereira 1991). The fire pixel counts are calibrated to area with burn scars mapped with Landsat. This direct estimate of burning is difficult and imprecise in the tropics due to frequent, and often persistent, cloud cover that makes for sparse Landsat calibration data and weak correlation between fire pixel counts and scar area, due to varying amounts of missing fire counts in the AVHRR product. The moderate resolution imaging spectroradiometer (MODIS) fire product has been developed, and the burn area mapping algorithm is currently being tested (Justice et al. 1998, 2002, Roy et al. 2002). The MODIS sensor provides near daily coverage at moderate resolution and the burn scar algorithm will provide additional information on the extent of biomass burning at some future time.

The objective of this research was to develop a method to quantify biomass burning emissions in the tropics at a local scale. This approach uses a novel indirect method, linking fire with land use, to estimate fire activity in the tropics rather than mapping active fires or fire scars. Using this method, for a forest area around Jamari, Rondônia, Brazil, we quantified area burned for 1984–1992; a period of early colonization and active deforestation in this region. Ground-based data were used to derive estimates of carbon emissions associated with the burned area (Guild 2000, Guild et al. 2004).

## Background

In the Brazilian Amazon, biomass burning emissions increased in the 1980s due to accelerated deforestation rates related to colonization projects that created fiscal incentives for agricultural expansion in remote areas of the Amazon (Molion 1991, Hecht 1993, Browder and Godfrey 1997). Traditionally, biomass burning is used to convert tropical forests to shifting agriculture, permanent agriculture, and/or cattle pasture. The primary land use driving force for deforestation has historically been for cattle pasture production because there is less labor involved in cattle ranching than in producing crops of rice, beans, corn, manioc, or tree crops. Further, cattle pastures are in continuous production longer (~10 yr) than crops (~2–3 yr). Shifting cultivation is typically a cycle of a 2-yr cultivation period followed by a 4-yr fallow period (Guild et al. 1998). In contrast to shifting agriculture that results in slash fires every 6 yr, pastures are burned purposefully or accidentally every 2–4 yr (Guild et al. 1998, Kauffman et al. 1998). Because of the frequency and extent, pasture burning could be a considerable source of carbon and other emissions to the atmosphere (Kauffman et al. 1998).

Burning associated with deforestation, land conversion, and pasture management in the Brazilian Amazon isn't only a source of regional air pollution. Biomass burning has been shown to decrease the pools of terrestrial ecosystem carbon and nutrients and result in increased susceptibility to fire of adjacent forested areas and fragments (Uhl et al. 1988, Fearnside 1990, Uhl and Kauffman 1990, Kauffman et al. 1995, 1998, Cochrane et al. 1999). Particularly limiting are data on losses of carbon and nutrients from burned sites. Mean nutrient losses from primary forest slash fires of the Amazon states of Pará and Rondônia are 88 Mg C/ha, 1181 kg N/ha, and 107 kg S/ha (Kauffman et al. 1995, 1998, Guild et al. 1998). Additionally, in livestock pasture fires of these states, mean nutrient losses are 14 Mg C/ha, 199 kg N/ha, and 16 kg S/ha (Kauffman et al. 1995, 1998, Guild et al. 1998). In terms of Amazon forest ecosystem vulnerability to fire, Cochrane et al. (1999) found increased fuel loading, decreased resistance to fire by previously burned forests, higher mortality of trees in more intense fires and recurrent fires, and increased susceptibility of trees to exposure ignition associated with adjacent fire-maintained areas (pastures and crops).

## Methods

### *Study area*

We examined land-use/land-cover change and fire emissions from 1984 to 1992 over a 94 370-ha area of primary forest in Rondônia, Brazil along the BR-364 highway. We chose to conduct our study in this region because of its relatively recent colonization and deforestation activity (cultivation, cattle pastures, timber exploitation, and mining) at the onset of our analysis and this allowed quantification of emissions that occur when tropical forest landscapes are colonized. In addition, data on prefire and postfire biomass, elemental pool dynamics, and fire chemistry were available (Kauffman et al. 1995, 1998, Guild et al. 1998, Hughes et al. 2000).

The study area includes the town of Jamarí, the Jamarí National Forest, subsistence farms and large ranches, and the Santa Bárbara tin mine and is centered at ~9°11′ S and 63°10′ W, ~100 km southeast of the state's capital, Pôrto Velho. The primary forest type of Rondônia and the study region is submontane open forest consisting of overstory broad-leaved canopy and subcanopy with an abundance of palms and vines (Departmento Nacional de Produção Mineral 1978, Instituto Brasileiro de Desenvolvimento Florestal [IBDF] and Instituto Brasileiro de Geographia e Estatística [IBGE] 1993, Cummings 1998). Soil types include red-yellow podzolic Latosols and red-yellow Latosols (Neill et al. 1997). Climatological data came from Pôrto Velho, Rondônia. Mean annual precipitation is 2354 mm (Departmento Nacional de Meteorologia, Brasil 1992). During the dry season, between June and September, mean precipitation is typically <100 mm/mo. Dry season mean temperature is ~25°C ranging from a minimum of ~21°C to a maximum of 31°C with a mean relative humidity of 85%.

### *Emissions model*

Gross emissions of CO, $CO_2$, $CH_4$, and hydrocarbon trace gases from biomass burning were computed following a model modified from that given by Chatfield et al. (1996) for biomass burning in Africa. This model is based on the rate at which fuel carbon burns per unit area and the weighted sum of emission factors for flaming and smoldering combustion (Lobert et al. 1991). We modified the emissions computation to include delineation of land-cover types and partitioning of biomass or fuel categories by land cover type. The mass of C for trace gas emissions from biomass burning is calculated as follows:

$$E_i = \sum_{l,k=1}^{l\max,k\max} (\eta^{f}_{il} f^{f}_{lk} + \eta^{s}_{il} f^{s}_{lk}) m_i c_l b^{AB}_{lk} f^{b}_{lk} a^{b}_{l} \qquad (1)$$

where $E_i$ is the mass of C in gas species $i$ emitted, emissions flux (Mg); $\eta^{f}_{il}$ and $\eta^{s}_{il}$ are flaming and smoldering emission factors for gas species $i$ by land cover type $l$ (g emission/g fuel burned); $f^{f}_{lk}$, $f^{s}_{lk}$ are the fraction of fuel burned from land cover type $l$ burned during flaming and smoldering combustion of fuel class $k$; $m_i$ is the mass of carbon in gas species $i$ (g C/g emission); $c_l$ is the carbon concentration (percentage) of biomass for each land cover type; $b^{AB}_{lk}$ is the total aboveground biomass (TAGB; g/ha) of fuel classes for land cover types; $f^{b}_{lk}$ is the fraction of biomass or fuel burned by land cover type and fuel class; and $a^{b}_{l}$ is the area of burn (ha) by land-cover type.

The emissions flux, $E_i$, of chemical species $i$ is calculated as the sum over distinct land cover types $l$. These land cover types include primary forest, regenerating forest, and pasture that were identified as the land cover type prior to detection of clearing in a Landsat-derived land cover change map for 1984–1992 (Guild 2000, Guild et al. 2004).

Emission factors for flaming and smoldering combustion, $\eta^{f}_{il}$ and $\eta^{s}_{il}$, for CO, $CO_2$, and $CH_4$ from two primary forest slash sites and one pasture site were acquired in collaboration with the SCAR-B project following methods of Babbitt et al. (1996) and Ward et al. (1992). Hydrocarbon emission factors measured for SCAR-B additionally follow methods used in Africa (Babbitt et al. 1996, Hao et al. 1996). Two to three fire-atmosphere sampling system (FASS) towers (Ward et al. 1992) at each site collected flaming and smoldering combustion phase gases using real-time analyzers and gas sampling in canisters (Babbitt et al. 1996). Real-time sensors measured CO and $CO_2$ with flaming and smoldering combustion phases measured sequentially based on time of duration of each phase of combustion from previous studies. Emission factors included CO, $CO_2$, $CH_4$, ethyne ($C_2H_2$), ethene ($C_2H_4$), ethane ($C_2H_6$), propyne ($C_3H_4$), propene ($C_3H_6$), and propane ($C_3H_8$) (Table 1). Emission factors for regenerating forests were not sampled during the SCAR-B experiment. Therefore, we used the primary forest emission factors for regenerating forests. Ward et al. (1992) measured emission factors for one second-growth forest in Pará in eastern Amazon, however, we chose not to use these emission factors because the relative emission factors estimated for the land cover types of this region of the Amazon are lower than those estimated for Rondônia.

It is important to compute separate flaming and smoldering emission factors since the carbon release rate depends strongly on phase of combustion (Ward et al. 1992). Weighting the emission factors for flaming and smoldering combustion yields a more representative estimate of emissions released from fire ignition to the end of the smoldering phase of combustion. Fractions of fuels consumed in flaming and smoldering phases of combustion, $f^{f}_{lk}$ and $f^{s}_{lk}$, were weighted by fuel category ($k$) for each site. Based on Ward et al. (1992) and observations of fuels burning in the Amazon, we assume that 90% of fine fuels (litter, dicot seedlings, rootmat, live and dead grass, attached foliage, and woody fuels <2.55 cm in diameter) are consumed by flaming-phase combustion and 10% in the smoldering phase. Intermediate fuels of 2.55 to 7.62 cm in diameter are equally (50%) consumed in the flaming and smoldering phases. For coarse woody fuels (fuel diameter ≥7.63 cm) and palms, 10% and 90% of the mass is consumed by flaming and smoldering combustion, respectively.

Mean TAGB from ground-based data collected between 1992 and 1995 in the study area was used for the aboveground biomass term, $b^{AB}_{lk}$ (Kauffman et al.

TABLE 1. Emission factors (mean ± 1 SE) for flaming and smoldering combustion in primary forest slash and pasture burning.

| Emission | Primary forest | | Pasture | |
|---|---|---|---|---|
| | Flaming (g/kg) | Smoldering (g/kg) | Flaming (g/kg) | Smoldering (g/kg) |
| CO (carbon monoxide) | 95.21 ± 5.32 | 169.21 ± 2.81 | 79.39 ± 5.97 | 174.10 ± 2.87 |
| $CO_2$ (carbon dioxide) | 1664.52 ± 9.60 | 1527.95 ± 4.95 | 1697.52 ± 10.66 | 1529.49 ± 4.95 |
| $CH_4$ (methane) | 5.46 ± 0.39 | 11.91 ± 0.21 | 2.93 ± 0.37 | 9.03 ± 0.18 |
| $C_2H_2$ (ethyne) | 0.27 ± 0.01 | 0.26 ± 0.01 | 0.24 ± 0.01 | 0.29 ± 0.01 |
| $C_2H_4$ (ethene) | 1.20 ± 0.06 | 1.53 ± 0.03 | 1.02 ± 0.07 | 1.45 ± 0.03 |
| $C_2H_6$ (ethane) | 0.66 ± 0.05 | 1.53 ± 0.04 | 0.32 ± 0.05 | 0.95 ± 0.04 |
| $C_3H_4$ (propyne) | 0.06 ± 0.01 | 0.07 ± 0.01 | 0.04 ± 0.00 | 0.08 ± 0.01 |
| $C_3H_6$ (propene) | 0.57 ± 0.04 | 1.01 ± 0.02 | 0.39 ± 0.05 | 0.86 ± 0.02 |
| $C_3H_8$ (propane) | 0.21 ± 0.02 | 0.51 ± 0.02 | 0.08 ± 0.01 | 0.27 ± 0.02 |

*Notes:* Values are from unpublished data collected during the 1995 Smoke, Clouds, and Radiation—Brazil (SCAR-B) Experiment (D. Ward, *personal communication*). Flaming-phase combustion emission factors are based on tower measurements recorded in the early stages of the fire, and smoldering emission factors of fuel consumed were recorded in the later stages of the fire.

1994, 1995, 1998, Guild et al. 1998, Hughes et al. 2000; Table 2). The biomass measured in each of these sites (or land-cover types, *l*) was partitioned into size classes and composition that differ in their influence on fire behavior. Biomass size classes, *k*, included litter, grass, dicot seedlings, root mat, attached foliage, fine woody debris, and coarse woody debris. Mean TAGB for primary forest sites in Rondônia is 343 Mg/ha, 116 Mg/ha for regenerating forests, and 79 Mg/ha for pastures (Kauffman et al. 1994, 1995, 1998, Guild et al. 1998, Hughes et al. 2000; Table 2). In the primary forests, the coarse woody debris comprises 69–89% of TAGB. However in the regenerating forests, coarse fuels represent 35–70% of TAGB, whereas 62–82% of TAGB is coarse fuels in pastures. The coarse fuels of primary forests and pastures, therefore, are the source of a greater quantity of the emissions generated than from fine fuels. The impact of coarse fuels on emissions from burning regenerating forest slash is more variable since there is much variation in these types of fuels at different stages of regrowth. In pastures, the coarse fuels are the remnant logs from original forests that remain in the sites and decompose slowly. This remnant coarse woody debris dominates by mass over the fine fuel components in pastures. Through pasture reburning and decomposition, the remnant logs continue to contribute to site emissions through time.

The proportion of biomass that is actually burned, $f^{b}_{lk}$ (combustion factor or efficiency), was measured at sites for the study area between 1992 and 1995 (Kauffman et al. 1994, 1995, 1998, Guild et al. 1998, Hughes et al. 2000). The mean combustion efficiency for all sites for each land cover type, *l*, was delineated by fuel type and calculated as: 48% for primary forest slash; 56% for regenerating forest slash; and 37% for pastures (Table 2).

A multidate land-cover type and change map was derived from a time series of Landsat Thematic Mapper (TM) data for the study area (Guild 2000, Guild et al. 2004). The TM data (30-m pixel resolution) consisted of dry season images for June 1984, July 1986, and July 1992 to decrease variability associated with phenology. Accuracy assessment of the classification with ground truth for a random stratified sample gave an overall accuracy of 79% and kappa statistic of 78% (Guild 2000, Guild et al. 2004). A contingency table (also known as a confusion matrix) was used for uncertainty analysis. The land-cover-change map indi-

TABLE 2. Mean total aboveground biomass (TAGB) and combustion factors for selected land cover types in Rondônia, Brazil (1992–1995).

| Land cover type | TAGB (Mg/ha) | Combustion factor (%) | Sources |
|---|---|---|---|
| Primary forest slash | | | |
| Range | 290–399 | 38–57 | Guild et al. (1998), Kauffman et al. (1994, 1995) |
| Mean ($n$ = 5) | 343 ± 19 | 48 ± 3 | |
| Regenerating forest slash | | | |
| Range | 71–178 | 47–63 | Hughes et al. (2000) |
| Mean ($n$ = 5) | 116 ± 17 | 56 ± 4 | |
| Pasture | | | |
| Range | 60–119 | 21–47 | Guild et al. (1998), Kauffman et al. (1994, 1998) |
| Mean ($n$ = 5) | 79 ± 14 | 37 ± 7 | |

*Notes:* Means are shown ±1 SE; $n$ is the number of sites.

TABLE 3. Primary and regenerating forest conversion and areas remaining in pasture in the Jamari, Rondônia study area (94 370 ha) in Brazil, 1984–1992 (Guild 2000, Guild et al. 2004).

| Land cover type | Area (ha) | Study area (%) |
|---|---|---|
| 1984–1986 | | |
| Primary forest clearing | 2 592 | 3 |
| Regenerating forest clearing | 615 | <1 |
| Area remaining clear (pasture) | 1 231 | 1 |
| 1986–1992 | | |
| Primary forest clearing | 7 352 | 8 |
| Regenerating forest clearing | 214 | <1 |
| Area remaining clear (pasture) | 2 692 | 3 |
| Cumulative area of pasture burned (2 yr) | 17 777 | NA |
| Cumulative area of pasture burned (3 yr) | 11 851 | NA |

*Note:* NA, not applicable.

cated change during a 2-yr period from 1984 to 1986 and a 6-yr period from 1986 to 1992. Each class identified the initial land cover type in 1984 along with land cover status in 1986 and 1992 to indicate timing of deforestation and clearing. For example, primary forest on one date followed by either regenerating forest or a site in a cleared state identifies a deforestation event between the two dates. A site remaining in a cleared state was indicative of pasture. Also, if a site was in a cleared state on an early date and then is showing regrowth on subsequent dates this would likely be a regenerating forest site or cultivation. There are numerous land cover change possibilities, but a time series of TM data along with knowledge of the land use practices allows reasonable identification of the land cover type and subsequent land use trajectory. The analysis of the land-cover-change map identified changes in land cover and indicated deforestation and clearing (i.e., burning) events for regenerating forests and pastures. From this map, area estimates of primary forest slash, regenerating forest slash, and pasture burns were quantified (Table 3).

### *Assumptions and approaches to model emissions*

Because of the selection of TM data (1984, 1986, and 1992) used, the change detection methodology does not allow detection of the actual timing of burning events within the 6-yr period between 1986 and 1992. These burning events included subsequent burns to maintain areas in pasture as of 1986. Precise timing of deforestation and subsequent burning was also missed during this time period. What can be quantified from the land cover change identified in the map is the following: (1) the total area of primary forest in 1986 that was deforested by 1992; (2) the area of regenerating forest in 1986 that was deforested by 1992; and (3) the amount of area that remained in pasture (cleared) since 1986 (Table 3). Estimating emissions based only on total areas cleared and burned for the 1986–1992 time period is likely an underestimate since pastures are maintained by frequent burning (approximately every 2–3 yr; Guild et al. 1998). In addition, consideration of subsequent burning following deforestation events is needed since these areas are deforested primarily for conversion to pasture, otherwise, emissions associated with reburning of pasture are overlooked.

To estimate pasture-burning emissions, we developed pasture-burning scenarios of frequent burning every 2 or 3 yr that account for the pasture burning practices representative of the region. The scenarios used to predict burning events for land cover types during the 1986–1992 time period were based on the assumptions that (1) deforestation of both primary and regenerating forest occurred at a constant rate; and (2) that pasture burning occurred every 2 yr to maintain pasture or from accidental burnings. Therefore, based upon the total area of primary forest cleared (7352 ha) between 1986 and 1992, we assume that deforestation occurred at an annual rate of 1225 ha or a little over 1% of the study area was deforested each year. In the same manner, regenerating forest area was cleared at the annual rate of 36 ha. Since pasture is the predominant reason for deforestation in the region, we made the assumption that both primary and regenerating forests were converted to pasture following cutting and burning and half of this cumulative area was burned each year. Forest area converted to pasture for the 1984–1986 time period is included in the area of pasture for the 1986–1992 time period. Additionally, due to the completion of the Samuel hydroelectric dam in 1989, there was forest and pasture lost to flooding of the Jamari River which runs adjacent to the BR-364 highway. Therefore, it was necessary to exclude these flooded areas as a source of potential burning emissions after 1988. Pasture area burned annually is calculated as

$$P_t = (0.5)(\mathrm{PA}_{t-1} + \mathrm{PF}_{t-1} + \mathrm{RF}_{t-1}) - \mathrm{PAF}_t - \mathrm{PFF}_t - \mathrm{RFF}_t \qquad (2)$$

where $P_t$ is the total area of pasture burned at year $t$; $\mathrm{PA}_{t-1}$ is the total area of pasture the previous year $t-1$; $\mathrm{PF}_{t-1}$ is the total area of primary forest cleared the

TABLE 4. Emissions equation (Eq. 1) parameters and associated value ranges used in the uncertainty analysis applying the Monte Carlo simulation.

| Description | Value | |
|---|---|---|
| | Mean | Range |
| CO emission factor, flaming, forest (g emission/g fuel burned) | 0.095 | 0.062, 0.138 |
| CO emission factor, flaming, pasture (g emission/g fuel burned) | 0.079 | 0.064, 0.099 |
| CO emission factor, smoldering, forest (g emission/g fuel burned) | 0.169 | 0.157, 0.193 |
| CO emission factor, smoldering, pasture (g emission/g fuel burned) | 0.174 | 0.168, 0.184 |
| $CO_2$ emission factor, flaming, forest (g emission/g fuel burned) | 1.664 | 1.585, 1.726 |
| $CO_2$ emission factor, flaming, pasture (g emission/g fuel burned) | 1.697 | 1.662, 1.725 |
| $CO_2$ emission factor, smoldering, forest (g emission/g fuel burned) | 1.528 | 1.488, 1.552 |
| $CO_2$ emission factor, smoldering, pasture (g emission/g fuel burned) | 1.529 | 1.512, 1.538 |
| $CH_4$ emission factor, flaming, forest (g emission/g fuel burned) | 0.005 | 0.003, 0.009 |
| $CH_4$ emission factor, flaming, pasture (g emission/g fuel burned) | 0.003 | 0.002, 0.004 |
| $CH_4$ emission factor, smoldering, forest (g emission/g fuel burned) | 0.012 | 0.011, 0.013 |
| $CH_4$ emission factor, smoldering, pasture (g emission/g fuel burned) | 0.009 | 0.008, 0.009 |
| Fraction of biomass burned, flaming, forest | 0.266 | 0.249, 0.293 |
| Fraction of biomass burned, flaming, pasture | 0.294 | 0.229, 0.394 |
| Fraction of biomass burned, smoldering, forest | 0.734 | 0.707, 0.751 |
| Fraction of biomass burned, smoldering, pasture | 0.706 | 0.606, 0.771 |
| Primary forest biomass (Mg/ha) | 343.26 | 290, 399 |
| Regenerating forest biomass (Mg/ha) | 115.96 | 71, 178 |
| Pasture biomass (Mg/ha) | 79.42 | 60, 119 |
| Combustion efficiency, primary forest | 0.48 | 0.38, 0.57 |
| Combustion efficiency, regenerating forest | 0.56 | 0.47, 0.63 |
| Combustion efficiency, pasture | 0.37 | 0.21, 0.47 |
| Primary forest area burned 1984–1986 (ha) | 2 854.43 | 2 109.17, 3 599.70 |
| Regenerating forest area burned 1984–1986 (ha) | 1 070.75 | 674.67, 1 466.83 |
| Pasture area burned 1984–1986 (ha) | 2 472.50 | 1 593.37, 3 351.64 |
| Primary forest area burned 1986–1992 (ha) | 6 813.43 | 5 525.75, 8 101.10 |
| Regenerating forest area burned 1986–1992 (ha) | 113.86 | 58.86, 168.85 |
| Pasture area burned 1986–1882 (ha) | 2 857.90 | 2 252.37, 3 463.43 |
| Cumulative area of pasture burned 1986–1992 (3 yr) (ha) | 11 402.54 | 10 329.48, 12 475.59 |
| Cumulative area of pasture burned 1986–1992 (2 yr) (ha) | 171 103.8 | 15 494.21, 18 713.39 |

*Notes:* For parameters measured on the ground, uniform random numbers were generated between the minimum and maximum sampled values. For area burned, random normal deviates were used, and the range is listed as 95% CI of estimated map category proportions. For cumulative area of pasture burned, random values from a uniform distribution were generated between the minimum and maximum area estimates from the pasture-burning model (Eqs. 2 and 3) using the estimated map category proportions for pastures.

previous year $t - 1$; $RF_{t-1}$ is the total area of regenerating forest cleared the previous year $t - 1$; $PAF_t$ is the total area of pasture lost to flooding at year $t$; $PFF_t$ is the total area of primary forest flooded at year $t$; and $RFF_t$ is the total area of regenerating forest flooded at year $t$.

For the 1986–1992 time period, the sum of the area of pasture burned, $P_{tot}$, is expressed as

$$P_{tot} = \sum P_t \tag{3}$$

where $t$ represents years 1986 to 1992.

For the second scenario, we assumed that pastures were maintained by burning every 3 yr. Deforestation rates remained linear as in the first approach. However, of the total area in pasture each year, we assumed that a third of this area burned and the equation for pasture area burned annually, $P_t$, is modified to divide by three instead of two.

### *Uncertainty and sensitivity analyses*

An analysis was conducted to evaluate the precision of the emissions estimate and the uncertainty associated with each of the parameters in the emissions equation (Eq. 1). The uncertainty analysis was performed using 1000 iterations of a Monte Carlo simulation allowing each of the parameters to vary in order to determine the influence of this variation on the model estimates. Variation of parameter values based on small samples were uniform random and variation of parameters based on large samples were pseudo-random normal. Most of the equation parameter values were uniform random numbers between the minimum and maximum measured sampled values (Table 4). For extents of our land cover types, we used pseudo-random normal values based on estimated map category proportions and standard deviations (Table 4), as calculated with the contingency table (confusion matrix) for the classified Landsat imagery (Card 1982). For cumulative area of pasture burned, the 95% confidence intervals of the estimated map category proportions were used to identify the minimum and maximum estimate of area for each land cover change class indicative of pasture. Then these minimum and maximum area estimates for pasture classes were used in the pasture area burned model (Eqs. 2 and 3) under both the 2- and 3-yr burning scenarios. The minimum and maximum cumulative

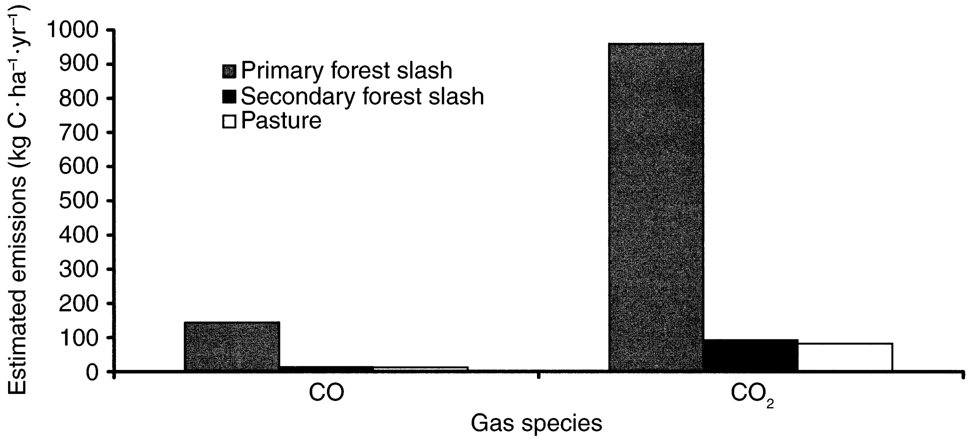


FIG. 1. Estimated emissions of CO and $CO_2$ from fires in primary forest slash, regenerating forest slash, and pastures for the extent of the Jamari, Rondônia, study area (1984–1986).

TABLE 5. Modeled estimates of emissions and mean emissions estimates (±1 SD) from the uncertainty analysis.

| Parameter | Modeled estimate of emissions ($kg\ C \cdot ha^{-1} \cdot yr^{-1}$) | Mean emissions from uncertainty analysis ($kg\ C \cdot ha^{-1} \cdot yr^{-1}$) |
|---|---|---|
| Primary forest (1984–1986) | | |
| CO | 144 | 165 ± 34 |
| $CO_2$ | 954 | 1056 ± 34 |
| $CH_4$ | 17 | 19 ± 4 |
| Regenerating forest (1984–1986) | | |
| CO | 13 | 25 ± 8 |
| $CO_2$ | 92 | 163 ± 52 |
| $CH_4$ | 1 | 3 ± 1 |
| Pasture (1984–1986) | | |
| CO | 12 | 26 ± 9 |
| $CO_2$ | 82 | 176 ± 62 |
| $CH_4$ | 1 | 2 ± 1 |
| Primary forest (1986–1992) | | |
| CO | 136 | 131 ± 24 |
| $CO_2$ | 907 | 837 ± 145 |
| $CH_4$ | 16 | 15 ± 3 |
| Regenerating forest (1986–1992) | | |
| CO | 1 | 1 ± <1 |
| $CO_2$ | 11 | 6 ± 2 |
| $CH_4$ | <1 | <1 ± <1 |
| Pasture (1986–1992) | | |
| CO | 9 | 10 ± 3 |
| $CO_2$ | 60 | 68 ± 22 |
| $CH_4$ | 1 | 1 ± <1 |
| Pasture (1986–1992, 3-yr burning) | | |
| CO | 38 | 39 ± 12 |
| $CO_2$ | 262 | 268 ± 80 |
| $CH_4$ | 3 | 3 ± 1 |
| Pasture (1986–1992, 2-yr burning) | | |
| CO | 57 | 59 ± 18 |
| $CO_2$ | 393 | 402 ± 122 |
| $CH_4$ | 5 | 5 ± 1 |

area of pasture burned for both the 2- and 3-yr burning scenarios were then used to identify the range of random values assuming a uniform distribution. The fractions of flaming and smoldering phases were held constant due to lack of data for estimating precision. Mean emissions estimates from the uncertainty analysis were calculated for the main gases CO, $CO_2$, $CH_4$. A sensitivity analysis was conducted to determine the effect of variation in the model parameters on the variation of the model estimates. The Monte Carlo simulation was iterated 1000 times for each of the parameters evaluated while holding the other parameters constant.

## RESULTS

### *Burning emissions for 1984–1986*

In the Jamari, Rondônia study area (94 370 ha), during the period of 1984 and 1986, the total flux of CO, $CO_2$, and $CH_4$ emissions from burning cut primary forest (2592 ha) were more than 10 times greater than from pasture burning (1231 ha) and that from cut regenerating forest burning (615 ha) (Fig. 1, Table 5) due to large biomass estimates per unit area and greater areal extent. Additional trace gas estimates of $C_2$ and $C_3$ hydrocarbon emissions for these land cover types include $C_2H_2$, $C_2H_4$, $C_2H_6$, $C_3H_4$, $C_3H_6$, and $C_3H_8$ (Fig. 2). Trends in these hydrocarbon trace gas estimates follow those of CO, $CO_2$, and $CH_4$, whereby emissions from primary forest burning dominate those from burning regenerating forests and pastures.

### *Burning emissions for 1986–1992*

The approximate annual flux of emissions from primary forest slash (7352 ha) for 1986–1992 was slightly lower than the 1984–1986 time period due to a 5% decrease in the average annual rate of deforestation from 1296 ha/yr to 1225 ha/yr in the 94 370-ha study area (Figs. 3 and 4, Table 5). Regenerating forest area (213 ha) burning emissions on an annual basis were

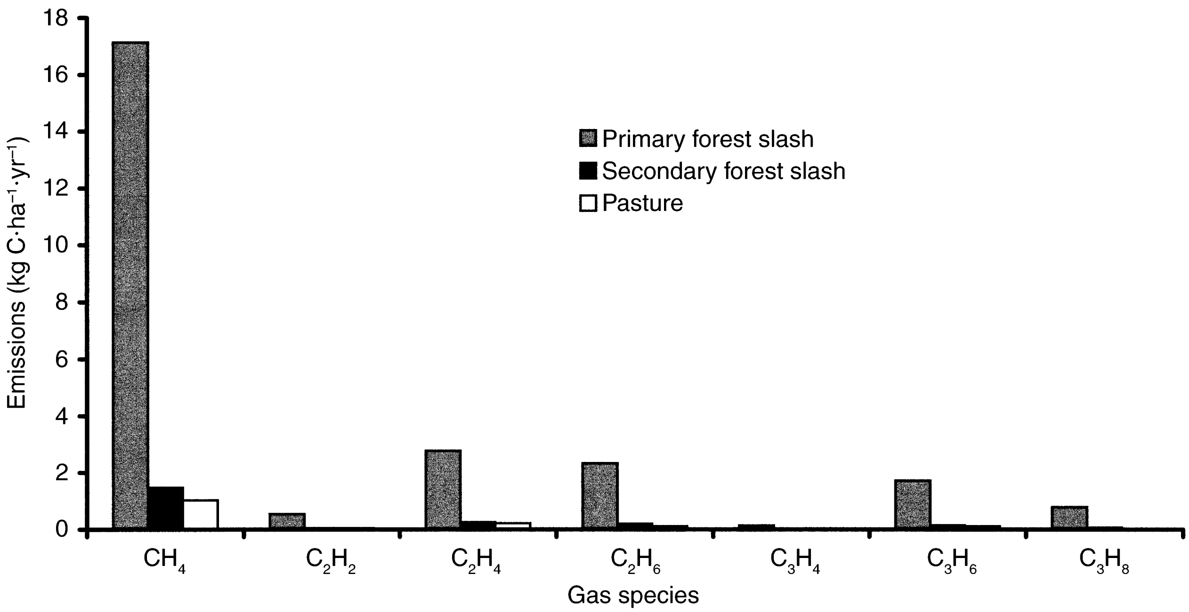


FIG. 2. Emissions of $CH_4$ and trace gases arising from fires in primary forest slash, regenerating forest slash, and pastures for the extent of the Jamari, Rondônia, study area (1984–1986).

over eightfold less than in 1984–1986. The contribution of emissions from fires in regenerating forests was substantially lower than from primary forest slash fires. This is attributed to the area in regrowth, which represented a small proportion (<1%) of the study area. This supports evidence of land use practices of the region of primary forests being deforested predominately for the creation of cattle pastures. Finally, for the area that was in pasture in 1986 and remained in pasture from 1986 to 1992 (2692 ha) and with the conservative assumption that this pasture area burned only once during this six year period, resultant emissions were 5–6% of primary forest emissions and four to six times greater than regenerating forest burning emissions.

Since realistically pastures are reburned frequently for maintenance and assuming that the predominant land use following deforestation was pasture we also estimated the cumulative area of pasture burned using a 2-yr and 3-yr burning frequency. Using the 2-yr burning scenario, the total area of pastures burned was 17 777 ha. This approach, which considers subsequent pasture burning following conversion of forest to pasture, indicates there was over a sixfold increase in the flux of C via CO, $CO_2$, $CH_4$, and hydrocarbon trace gas emissions from pastures burned only once (Figs. 3 and

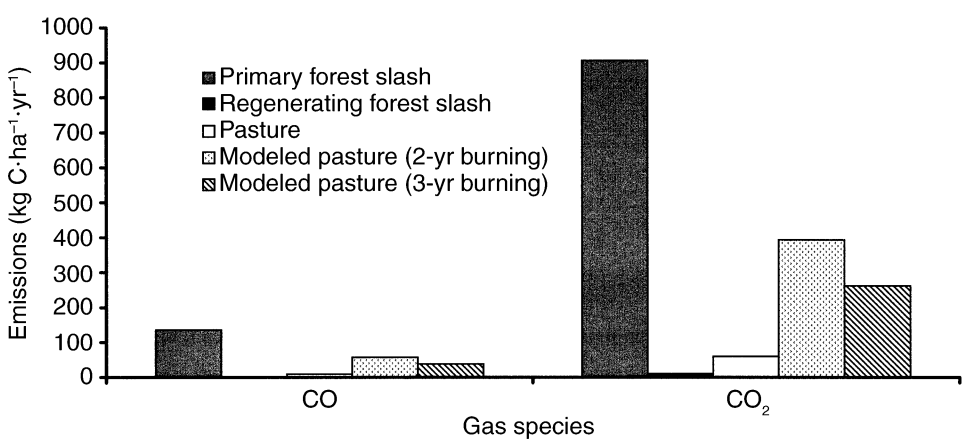


FIG. 3. Emissions of CO and $CO_2$ arising from burning primary forest slash, regenerating forest slash, and pastures (burned once) for the extent of the Jamari, Rondônia, study area (1986–1992). Modeled pasture emissions include pastures reburned on a frequency of 2 or 3 yr during the study period.

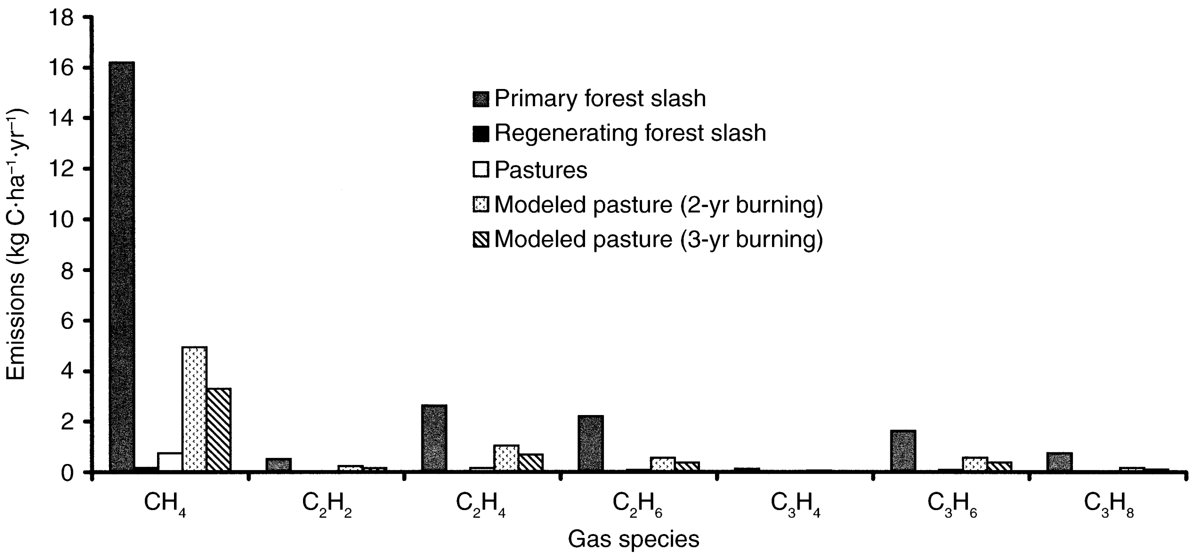


FIG. 4. Emissions of trace gases from burning primary forest slash, regenerating forest slash, and pastures (burned once) for the extent of the Jamari, Rondônia, study area (1986–1992). Modeled pasture emissions include pastures reburned on a frequency of 2 or 3 yr during the study period.

4, Table 5). In comparison to annual pasture emissions from 1984 to 1986, there was nearly a fivefold increase on an annual basis during the 1986–1992 time period. The pasture area burned during this period was over twice the area deforested, but the total quantity of pasture emissions was half that from primary forest slash burning. The relatively higher TAGB and the combustion factor of primary forest slash sites of the region are the primary factors influencing the higher mass of carbon emissions from these sites.

If pastures were burned on a 3-yr cycle, calculated as one-third of the area in pasture is burned each year, the total area of pasture reburned was 11 851 ha. In contrast to just considering the area in pasture burning once and excluding forest conversion to pasture, this 3-yr pasture-burning cycle represents about a threefold increase in mean C fluxed annually through CO, $CO_2$, $CH_4$, and hydrocarbon trace gas emissions (Figs. 3 and 4, Table 5). In comparison to the 1984–1986 pasture emissions on an annual basis, the mean emissions during the 1986–1992 period were about three times greater. The area of primary forest slash burned was ~60% that of pasture burned in this 3-yr reburning scenario, however, the quantity of pasture burning C emissions was <30% of primary forest slash emissions.

Using the 2-yr burn assumption to estimate pasture emissions during the 1986 to 1992 time period, the contribution of emissions from reburning areas in pasture was clearly more important as a source of emissions from burning in the study area. It is apparent from our calculations that the magnitude of emissions is likely underestimated if there is no consideration of pasture areas reburning. Additionally, by including deforested areas into the pasture area pool for reburning, a supplementary source of emissions contributed to the pasture emissions estimates.

Trace gas estimates for $C_2$ and $C_3$ hydrocarbon emissions, from primary and regenerating forest slash and pasture burning during the 1986 to 1992 time period, maintain the trends (primary forest dominating) in the magnitude of the flux of these emissions between land cover types (Fig. 4). Hydrocarbon emissions of ethene ($C_2H_4$), ethane ($C_2H_6$), and propene ($C_3H_6$) were higher than ethyne ($C_2H_2$), propyne ($C_3H_4$), and propane ($C_3H_8$). These hydrocarbon gases remain at trace levels in comparison to CO, $CO_2$, and $CH_4$.

### *Gross burning emissions for the entire 1984–1992 study period*

During the entire time period of this study (1984–1992), total carbon released in the 94 370 ha (~944 km$^2$) study area from primary forest slash burning (9944 ha) was 817 086 Mg C or $8.0 \times 10^{11}$ g C (1082 kg C·ha$^{-1}$·yr$^{-1}$ or 108 227 kg C·km$^{-2}$·yr$^{-1}$) in carbon gases estimated (Figs. 5 and 6). Regenerating forest slash burning (827 ha) contributed 27 225 Mg C (36 kg C·ha$^{-1}$·yr$^{-1}$ or 3606 kg C·km$^{-2}$·yr$^{-1}$) in carbon gases. Including the forests converted to pasture under the 2-yr burn return interval, the cumulative area of pasture burned was 19 008 ha between 1984 and 1992. The carbon flux from pasture burning was 277 416 Mg C or $3.0 \times 10^{11}$ g C (367 kg C·ha$^{-1}$·yr$^{-1}$ or 36 745 kg C·km$^{-2}$·yr$^{-1}$). The magnitude of the primary forest emissions was three times that of burning emissions from pastures. However, the area of primary forest area burned for the study period was 9944 ha, whereas 19 008 ha of pasture burned, nearly double the area of primary forest burned.

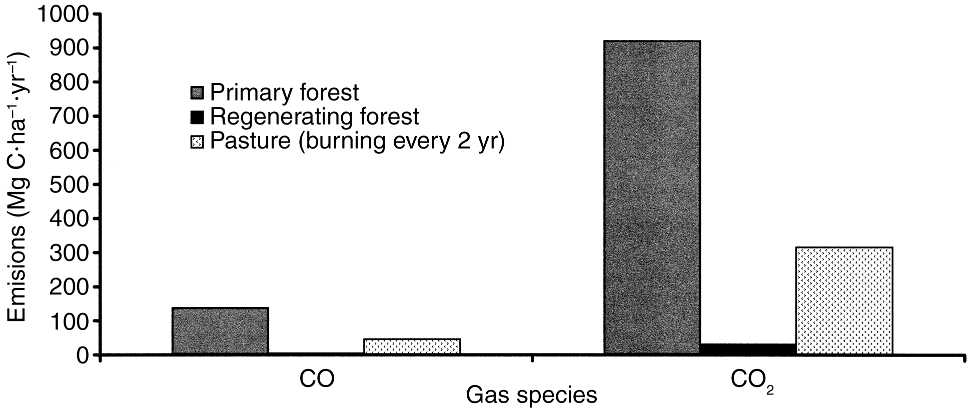


FIG. 5. Emissions of CO and $CO_2$ arising from burning primary forest slash, regenerating forest slash, and pastures for the extent of the Jamari, Rondônia, study area (94 370 ha) during the study period (1984–1992). Pasture emissions include pastures burned between 1984 and 1986 and modeled pastures reburned on a frequency of 2 yr for the 1986–1992 period.

### *Uncertainty and sensitivity analyses*

From the uncertainty analysis, the influence of varying parameters on the model estimates of emissions showed that the model estimates of regenerating forest and pasture emissions between 1984 and 1986 were likely underestimated (Table 5). Otherwise, the emissions model performed well and was within range of the estimates from the uncertainty analysis. Uncertainty in gross emissions estimates from primary forest burning was predominantly due to uncertainty of combustion efficiency and area burned as shown in the sensitivity analysis (Table 6). Variation in estimates of gross emissions from burning regenerating forests was primarily due to biomass estimates and secondarily by area burned. Pasture-burning emissions estimates were shown to be influenced largely by biomass and combustion efficiency. Further, when considering reburning of pasture for pasture maintenance, the variation allowed for the cumulative area burned parameter decreased the variability in the emissions estimation.

## DISCUSSION

Our estimates of gross carbon emissions from deforestation and pasture burning are based on an area of early colonization (i.e., low proportion of landscape deforested) in Rondônia. The expansion of land cover in cattle pasture occurred steadily as active deforestation converted forests to pasture during the time period of this study. With increasing area in pasture as well as frequent reburning of pastures, the mounting importance of pastures in the contribution of gross emissions is revealed in our results. The annual flux of

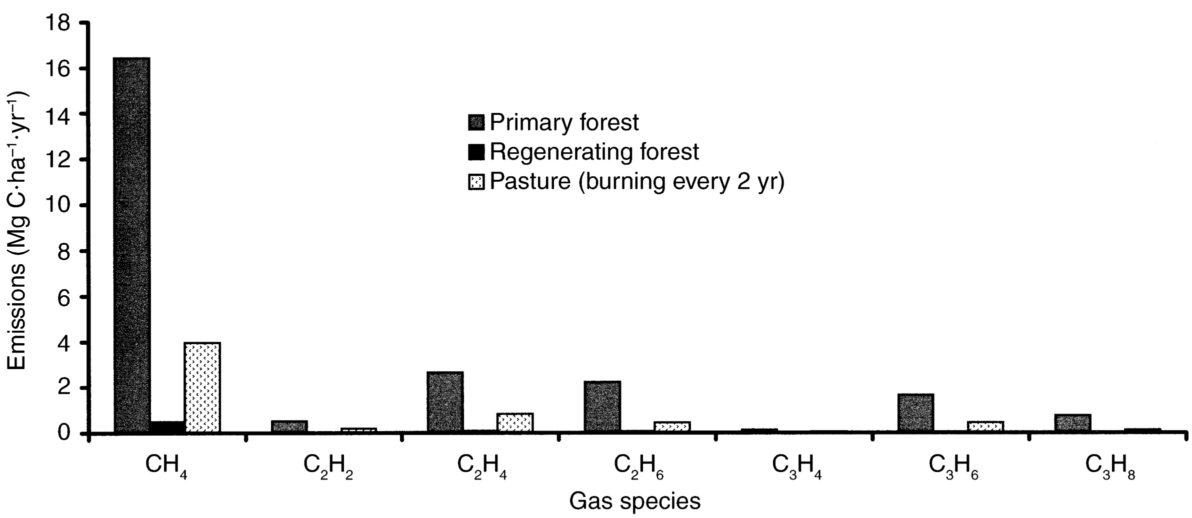


FIG. 6. Emissions of trace gases arising from burning primary forest slash, regenerating forest slash, and pastures for the extent of the Jamari, Rondônia, study area (94 370 ha) during the study period (1984–1992). Pasture emissions include pastures burned between 1984 and 1986 and modeled pastures reburned on a frequency of two years for the 1986–1992 period.

TABLE 6. Sensitivity analysis results of variation in emissions estimates based on varying each of four emissions-equation variables while holding the other factors constant.

| | Variation (%) | | |
|---|---|---|---|
| Parameter varied | 1984–1986 | 1986–1992 | 1986–1992 (2–3-yr pasture-burning frequency) |
| Emission factor | | | |
| Primary forest | 1–10 | 1–13 | |
| Regenerating forest | <1–4 | <1–3 | |
| Pasture | 3–4 | 4–5 | 4–5 |
| Biomass | | | |
| Primary forest | 19–22 | 24–30 | |
| Regenerating forest | 62–68 | 49–53 | |
| Pasture | 33–35 | 40–42 | 46–50 |
| Combustion efficiency | | | |
| Primary forest | 28–33 | 37–45 | |
| Regenerating forest | 5–6 | 4–5 | |
| Pasture | 30–33 | 40–43 | 41–44 |
| Area burned | | | |
| Primary forest | 38–44 | 26–31 | |
| Regenerating forest | 27–30 | 37–40 | |
| Pasture | 21–23 | 10–11 | 2–3 |

*Notes:* Monte Carlo methods and 1000 iterations were used. The range of the percentage of this variation to total variance (all factors varying; see Table 4) of the emissions equation is reported.

carbon emissions from frequent pasture burning between 1986 and 1992 was five times greater than the annual flux between 1984 and 1992. The total flux of pasture emissions between 1986 and 1992 was about half that from primary forest burning. This is substantial, given that ~14% of the study area had been cleared as of 1992 and 8% of that was due to primary forest clearing between 1986 and 1992.

### *Extrapolating biomass burning emissions modeling to the state of Rondônia*

Annual rates of deforestation for Rondônia, excluding areas of forest flooded by hydroelectric dams, were 2100 km$^2$ (1978–1988), 1400 km$^2$ (1988–1989), 1700 km$^2$ (1989–1990), and 1100 km$^2$ (1990–1991) (Fearnside 1997). These deforestation rates were 4%, 8%, 12%, and 10%, respectively, of the total for the legal Amazon's annual deforestation rates, indicating an increasing trend of annual deforestation. As of 1991, 16% (34 200 km$^2$) of Rondônia's original forest area (215 000 km$^2$) had been deforested (Fearnside 1997). By using Fearnside's annual deforestation rates and assuming that 1100 km$^2$ was also the annual deforestation rate for 1991–1992, we estimated that 12 700 km$^2$ (1 270 000 ha) of primary forest in Rondônia was cleared between 1984 and 1992. Using this deforestation area estimate in the emissions computation, the mass of C emitted was $1.3 \times 10^{13}$ g C in CO, $8.9 \times 10^{13}$ g C in $CO_2$, and $2 \times 10^{12}$ g C in $CH_4$. To calculate emissions from pasture fires in Rondônia, we assumed that each year during the 1978–1992 time period, the forest area cleared was converted to pasture and half the area in pasture was burned each year. We summed the total area of pasture burned for 1984–1992 (corresponding to our study period). C flux was estimated as $1.5 \times 10^{13}$ g C in CO, $1.06 \times 10^{14}$ g C in $CO_2$, and over $1 \times 10^{12}$ g C in $CH_4$. Here, it is evident that pasture emissions rivaled emissions from deforestation between 1984 and 1992.

Although emissions from fires of slashed primary forest decreased due to declining deforestation rates in Rondônia between 1978 and 1992, the quantity of emissions generated from fires to maintain pasture likely increased with the continued expansion of the areal extent of pastures each year. Hence, the conversion of forests to pastures represents a potential long-term source of emissions that has received little attention. Consideration of these anthropogenic sources of emissions is essential for reporting regional and Amazon emissions estimates.

### *Comparison of methods with previous Amazon-wide burning-emissions estimation*

Early estimates of Amazon burning emissions by Setzer and Pereira (1991) use a basic method adapted from Seiler and Crutzen (1980) to quantify the mass of dry biomass burned. This calculation multiplied area of forest and cerrado (Brazilian savanna) burned by average biomass and combustion factor for each vegetation type. The mass of emissions is assumed to be 45% of the mass of biomass burned. In comparing Setzer and Pereira's parameters and our input parameters into the respective emissions calculations, the differences of concern are the use of AVHRR to estimate area burned by land cover type and the estimates of emission ratios based on aircraft sampling. First, there is some error associated with the resolution of the AVHRR pixels (1.1 km) in estimating area burned, but for burn-area estimates for the entire Amazon, AVHRR is suitable (Setzer and Pereira 1991). Secondly, aircraft sampling could represent a mixture of emissions from adjacent or nearby fires. Our use of emission factors from ground-based tower measurements likely eliminates most of this error associated with mixing of emissions at higher altitudes. In addition, delineating the contribution of flaming and smoldering combustion to emissions in our approach should provide more accurate emissions estimates.

### *Comparison of methods with a local-scale burning-emissions estimation*

Fujisaka et al. (1998) estimated carbon emissions based on aboveground (trees, understory, and charcoal) and belowground (roots and soil) carbon stock losses associated with deforestation in the area of Theobroma, Rondônia. These carbon emissions are calculated as the carbon stock of the original forest area subtracted by the carbon stock of the area estimates of replacement land use vegetation (i.e., pasture, fallow, and annual crops). In the 216 500-ha study area, 93 211 ha (43% of the study area) was deforested by 1993 with carbon emission estimate of $1.4 \times 10^{13}$ g over a 20-yr period (1973–1993). On an annual basis for the Theobroma study area, carbon emissions associated with deforestation and land use were approximately 3 Mg $C \cdot ha^{-1} \cdot yr^{-1}$. For our 94 370-ha study area, of which only 14% was deforested by 1992, our total carbon emissions estimate was nearly 2 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ and this estimate includes reburning of pasture areas. The forest and fallow aboveground carbon stocks used in the Theobroma study were within the range for our primary and regenerating forest measurements, but the aboveground pasture carbon stocks for our estimates were fivefold greater than those used in the Theobroma study. In the Theobroma study, belowground carbon stocks were 16–45% of the total forest, annual crop, and fallow crop carbon stocks. However, belowground carbon stocks in pasture were 69% of the total pasture carbon stock. The differences between the Theobroma study and ours are likely due to the amount of area deforested in the study area and not from the estimates of carbon stocks. The total of aboveground and belowground carbon stocks in the Theobroma study were within the range of, or close to our estimates of aboveground carbon stocks by land cover type. Theobroma is an area subjected to widespread land-cover/land-use change for a longer time period. Also, the Theobroma study assumed that the differences between carbon stocks of forest and resultant land uses were carbon emissions.

### *Caveats*

The shortcomings of our research are that there are additional sources of emissions that arise from the land-use/land-cover change areas besides those directly from combustion not estimated by our techniques. For example, there are emissions associated with decomposition by microbes and termites of uncombusted biomass from the original forest and regrowth found in pastures and regenerating forests over a 10-year period (Fearnside 1997). During this period, 42% of the aboveground biomass carbon was released through combustion and 56% through decomposition. The remaining biomass carbon was found in charcoal remains (<2% of prefire carbon pools) from burning slash and results in long-term carbon pools in the soil. Additionally, reburning of coarse wood in pasture sites increased the on-site charcoal carbon pools. Not directly related to biomass burning, but associated with pastures is the production of $CH_4$ by cattle. Globally, ruminants produce 15–20% of the total $CH_4$ emissions and; therefore, are an important source of $CH_4$ emissions (Leng 1993). Methane production by ruminants is not addressed in this research.

In addition to aboveground carbon, there are emissions estimates associated with belowground carbon (Fearnside 1997, Fujisaka et al. 1998). We did not include belowground carbon emissions from decomposition and processes influenced by burning and heating of soil. Fearnside (1997) assumed that all carbon released from soils is $CO_2$ and that the greatest release occurred near the surface (i.e., top 20 cm of soil). An additional belowground carbon source for $CO_2$ emissions included in Fearnside's (1997) emissions is belowground decay. Fearnside termed emissions as ''net committed emissions'' where sources of carbon emissions include, initial forest burn, pasture reburning, termites and decomposition (aboveground and belowground), soil carbon, and cattle. Although Fearnside's approach and scale of emissions estimates is different and not appropriate for comparison with our methods, the discussion of the inputs into Fearnside's calculation is important to address. For example, in quantifying burning emissions Fearnside used TAGB, burning efficiency, releases by reburning, and flaming and smoldering burn releases (for trace gases). Some of the ground-based measurements that we used were also used by Fearnside. In contrast, we include flaming and smoldering burn release for all gases estimated and additionally our methods use emissions factors.

### *Future research*

The methods presented in this research could be applied to other states in Amazonia to extrapolate local ground-based measurements to estimate state biomass burning emissions and ultimately improve Amazon Basin biomass burning emissions associated with land use. To accomplish this, appropriate ground-based data on emission factors, TAGB, and combustion factors would need to be integrated with regional deforestation and land clearing estimates. We assumed that for this study, the ground-based estimates of TAGB, combustion factors, and emission factors were representative of the primary forests, regenerating forests, and pastures of the study area. However, based on our uncertainty analysis, better data on biomass and combustion efficiency would improve estimates of gross emissions from pastures, in particular.

As measurements of TAGB and combustion factors will likely change with age of pasture and age of regenerating forest, for example, we assumed the different ages of pastures and second-growth and third-growth forests sampled in the ground-based measurements captured these differences. This could be an area of further investigation. Additionally, the confusion of delineating pastures and regenerating forests between two dates and only two years apart is difficult. Clarification of these classes is further understood by monitoring a longer time period to determine the clearing frequency. Longer periods of regrowth (∼4 yr or more) indicate regenerating forest or cultivation.

Despite high rainfall in moist tropical forests of the Amazon, seasonal drought is prevalent. Further, severe drought events associated with El Niño, occurring during seasonal drought, limits carbon gain and increases flammability. Fire activity increases during El Niño years enhancing the magnitude of burning emissions generated. Further study of ground-based measurements of fire chemistry and combustion during severe drought events may provide improved data for emissions computations. Also, more frequent collection of remote sensing data during severe drought events could better identify fire activity and area burned to improve burning emissions estimation.

We found that area estimates of deforestation and land clearing are better captured in a temporal series of satellite data at a frequency to adequately capture change rather than from single-date analysis (Guild 2000, Guild et al. 2004). For Rondônia and other areas of the Amazon where pasture burning is persistent, frequent intervals of data selection could improve estimates. In other areas of the Amazon where forest conversion and pasture burning is less frequent, the time interval for data selection might be on the order of every 4–6 years or longer. In areas where shifting cultivation and/or cattle ranching is intense, a well documented knowledge of the land use and burning practices would decrease uncertainties in burning predictions when adequate satellite or aircraft data is unavailable. Agricultural agencies of the region and landowner interviews could provide the land use history needed to make predictions of land use practices that influence C flux (e.g., burning scenarios). Addressing the contribution of biomass burning emissions associated with agricultural practices at an appropriate scale will improve the accuracy of the contribution to changes in the atmospheric carbon balance.

For our study area describing a period of early colonization, the greatest emissions sources were attributed to those arising from fires in primary forest slash, but the frequency of pasture burning also produced a considerable flux of emissions. Using 1978–1991 deforestation estimates of Fearnside (1997), we found that in cattle-ranching-dominated land-use systems following deforestation, pasture burning emissions rival deforestation burning emissions. Also, with areas in pasture increasing, forested area would become increasingly fragmented. Forest edges and fragments become more susceptible to surface fires escaping from pasture and slash fires contributing to additional elemental pool losses and burning emissions. Increased disturbance elevates losses in carbon and nutrient pools, decreases the capacity of the ecosystem to function as a carbon sink, and in time renders the system unproductive.

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